CHAPTER 1 INTRODUCTION

This study was undertaken in response to a critical need expressed by the State of Hawaiʻi's Dept. of Land and Natural Resources, Division of Aquatic Resources. As managers of the state's marine resources, this agency is mandated by federal law to protect and manage Hawaiʻi's waters, including over 410,000 acres of coral reefs. In order to achieve their goals of conservation and sustainability, they have established areas of concern and pressing problems. These include overfishing, introduced species, eutrophication, sedimentation, pollution and overuse. One issue relating to overuse, nearshore trampling damage, was identified as a major concern in establishing sustainability at popular tourist destinations.

Data evaluating anthropogenic impacts is vital to properly manage these resources, yet research on these impacts is sparse. Quantitative research evaluating the physical and biological impacts of trampling in Hawaiʻi are almost non-existent. Harrington (1999) provides a qualitative assessment of damage to corals at Kahaluʻu on the Island of Hawaiʻi.

The research conducted in this study addresses the need for quantified data on which to base management decisions. The objectives of this research are consistent with that need.

1.1   **<u>Objectives</u>**

The objectives of this thesis are to quantify the impacts to corals caused by trampling. The fulfillment of the following objectives were realized through *insitu* and laboratory controlled experimentation.

- Demonstrate whether or not there are impacts to coral reefs by skin divers and waders.
- Determine the degree of coral mortality directly related to these impacts.
- Evaluate the growth rates of coral subjected to trampling.
- Establish baseline data for two popular skin diving sites.
- Provide a baseline for potential damage at other areas of concern throughout the state.
- Determine breakage strength and rates for dominant Hawaiian corals.

1.2   **<u>Hypotheses</u>**

These hypotheses outline the predicted outcomes of this project.

- Significant negative impacts to corals will be demonstrated at the high use site.
- Mortality of corals will increase with increased skin diving activity.

- Growth rates of corals and increased human use are inversely related.

- Recovery of Hawaiian corals from trampling damage is rapid once the impact has been removed.

- Corals with highly branched morphology possess lower skeletal strength than massive, lobate forms.

1.3   Experimental Design

With the complexity of coastal marine ecosystems and spatial and temporal variation, it is extremely difficult to isolate specific impacts. This study was specifically designed to quantitatively address the impacts to corals by skin divers and waders by incorporating several levels of experimentation that collectively address these impacts. Three main investigations strengthen the experimental design.

1) Community level studies evaluate linear growth rates and mortality, determined through coral transplantation into sites that range along a gradient of human use (Chapters 2,3).

2) Colony level experiments control for all factors affecting growth and mortality. Simulated trampling was conducted under experimental conditions to determine the rates of growth, mortality, and recovery of dominant Hawaiian corals subjected to trampling damage (see Chapter 4).

3) Skeletal strength and breakage rates were also quantified under laboratory controlled conditions (see Chapter 5).

Community level studies (1) were linked to controlled colony level experiments (2) to establish the causal relationship between coral growth and mortality and impact from trampling. Laboratory breakage tests (3) confirmed rates of fragmentation during field experiments, with species strength remaining consistent throughout all investigations.

Ideal conditions for the study of the impact of humans on coral reefs would support randomization, replication of treatments and multiple control sites. This is not always possible in large-scale community level experiments (1). Sites can not be randomized as in controlled experimentation. Sites must be selected based on the degree of impact. Yet, relationships between ecological distance and gradients of human impacts can be a quantified measure of the extent of damage (Bernstein and Smith 1986). The emphasis is usually on post-impact studies. Most human impact research begins after the impact has commenced. Without prior data, naturally caused losses may not be accounted for by simply comparing impacted and non-impacted sites. Data collected before the impact is difficult to obtain since predictability is often not possible. Since environmental conditions vary both spatially and temporally, replication and multiple control sites would also lack homogeneity. These factors can create interference in detecting anthropogenic impacts when comparing impacted experimental stations with non-impacted control stations. To provide the evidence necessary to establish a cause and effect relationship between trampling damage and growth or mortality, these large-scale community level experiments (1) must be combined with small-scale manipulative experiments (2).

Causal relationships between biological variables and human activity can be established through isolation of the treatment, and control of other factors affecting coral growth and mortality. Small-scale experiments can often establish causal links (2). To determine survivorship of corals, the probability of the survival of colonies and fragments subsequent to exposure to treatment can be compared to colonies and fragments in the control group, not exposed to damage by trampling under the same environmental conditions (Liddle and Kay 1987).

Response to trampling at the community level was addressed through the large-scale study involving the growth and mortality of corals at sites that ranged along a gradient of human use (1). To determine if the relationship between growth of corals and human activity is causal, experimental manipulation is required (2). The simulated trampling experiment provided a quantitative baseline to compare the response of trampling of four dominant Hawaiian coral species at the colony level. Restricted on spatial and temporal scales, it can help affirm the link at higher scales by isolating the experimental factor and controlling for other physical, chemical and biological variables that can affect coral growth and mortality, such as light, turbidity, salinity, temperature, water motion and depth. Single population measurements can be causally linked directly to the impact and may be more sensitive indicators than community level measures. Experimental manipulation providing evidence of causal links between the variable measured and the impact can thus strengthen community level studies (Keough and Quinn 1991).

The skeletal strength of the four species of common Hawaiian corals used in the simulated trampling experiments (2) had not previously been established. Thus, laboratory, mechanical tests were conducted (3) to relate the resistance of corals to applied force, to the breakage that occurred in controlled trampling (2).

The amount of damage incurred from trampling or natural forces in nearshore environments is related to the skeletal strength of various coral species and growth forms. High skeletal strength may be an adaptive response that reduces breakage and mortality caused by disturbance.

1.4   **Background Information**

Globally, the topography of present reefs was inherited from an earlier period. Today's coral reefs are just a thin veneer overlaying older, eroded reef structures from the Pleistocene period. This has been evidenced from deep drilling in Pacific atolls and the Great Barrier Reef (Stoddart, 1973; Scoffin et al., 1978). Grigg (1998) confirms this locally by measuring vertical reef accretion at four sites in the main Hawaiian Islands.

Coral reefs are the ocean's version of the tropical rainforest, containing some of the oldest and most biologically diverse ecosystems on earth. The Hawaiian archipelago is the most isolated in the world, with the closest continent lying more than 4000 km away and the nearest island group more than 1600 km. This geographic isolation has resulted in some unique characteristics of our coral reefs.

Reef building corals in the Hawaiian Islands are highly depauparate compared to the rest of the Indo-West Pacific. The coral populations in Hawai'i are comprised of only 42 species belonging to 16 genera. Although species diversity is low, endemism of Hawai'i's marine organisms is exceptionally high.

Much research has been conducted on the biogeography of recent reefs (Stoddart, 1971, 1984; Maragos, 1974; Scoffin et al., 1978; Grigg, 1983). The dominant controlling factors of community structure and growth of corals are natural forces (Highsmith et al., 1980). Wave exposure is the major forcing function controlling coral accretion rates. Grigg (1983) found that anthropogenic impacts can compound these effects and dominate where wave exposure is limited, as in protected shoreline regions including lagoons and bays with high residence time and poor water circulation. Coral community structure in Hawai'i is also primarily controlled by wave energy, with only about 10% of the coastline not impacted by waves (Grigg 1998). Yet, most reefs are located in deeper, offshore waters that have the least exposure to anthropogenic impacts.

Hawai'i is dependent on coral reefs for their intrinsic, aesthetic, recreational, medicinal, scientific, educational and economic values. Reefs protect our coastlines from damaging storm surf. They provide habitat, shelter and food resources for many marine organisms.

Human induced impacts have increased with the advent of modern transportation technology, higher standards of living and population expansion. Tourism and its associated research have accompanied this growth (DBEDT

1998, Hawaiʻi Coastal Zone Management 1998, Hawaiʻi Tourism Marketing Council, Hawaiʻi Visitors Bureau Statistics 1980-1997).

In recent years, an increasingly popular concept has been integrated into the tourism industry. "Ecotourism" is a term applied to visitor activities that provide a terrestrial or aquatic wilderness experience (Magnuson1993, Fullard-Leo 1996, Essoyan1997, Kitchen 1995, 1999). Ecotourism is growing worldwide and in Hawaiʻi.

Here in Hawaiʻi, anthropogenic impacts on reefs have been linked to the tourism industry. Hawaiʻi receives over 7 million visitors a year, 85% of which use the nearshore resources (Hawaiʻi Visitors Bureau Statistics 1980-1997). Barrus (1995) acknowledges the negative impact on the environment and the social consequences involved in ecotourism. There are increasing concerns about sustainability and carrying capacities that have generated research within the industry (Hawaiʻi State Office of Planning 1991)

Anthropogenic impacts to coral reefs have been reviewed by Stoddart, (1981); Hatcher, (1989); UNESCO, (1985); and Tilmant, (1987). Research completed to date focuses on diverse human induced impacts including studies on sedimentation (Te, 1997), introduced species (Russell, 1981, 1983, 1992; Glenn and Doty, 1989; Eldredge, 1994; Rodgers and Cox 1999), sewage and eutrophication (Smith et al., 1973; Hunter and Evans, 1995; Laws and Allen, 1996; Larned, 1998) and various other problems associated with human use.

Stoddart (1972) describes general, *in situ* methods used in evaluating coral reefs. Keogh and Quinn (1991) focused more specifically on methodology

8

for detecting human impacts to reef environments, while Brown et al. (1999) conducted their research in Thailand, evaluating benthic sampling methods.

To evaluate growth differences in coral between disturbed environments and reference conditions, measuring coral growth rates is one of the most effective measures of determining stress due to disturbance (Birkeland et al.1976). Researchers have successfully used the Alizarin red method of staining (Hudson 1981, Dodge et al. 1984, Brown et al 1985). Methodology for more specific measurements of water motion (McConnel and Siegler 1959, Muus 1968, Doty 1971, Jokiel and Morrissey, 1993), temperature (Jokiel and Coles, 1990), and power analyses (Sheppard, 1999; Brown et al., 1999) describe more specific methods for quantifying parameters surrounding coral reefs.

Numerous physical and chemical factors influence the growth and survivorship of corals. Abundant research exists linking temperature (Coles and Jokiel 1977, 1978, Jokiel and Guinther 1978, Hudson 1981, Coles 1985), salinity (Muthinga and Szmant 1987, Coles and Jokiel 1992, Moberg et al. 1997, Ferrier-Pages et al. 1999), light (Kirk 1985, Falkowski et al. 1990, Rogers 1990, Miller and Cruise 1995, Te 2000), and water motion (Glenn and Doty 1992, Jokiel and Morrissey 1993) to the physiology of coral. These elements can also interact to produce synergistic effects with sub-lethal and lethal consequences for corals (Yonge and Nichols 1931,Jokiel and Coles 1977, Coles and Jokiel 1978, Egana and DiSalvo 1982).

A large percent of Hawai'i's reefs are easily accessible to the human population, located within close proximity of major urban centers of resident and

9

tourist concentration. Anthropogenic impacts to reefs are thus greatly increased (Gulko 1999). Increased human population pressure on coral reefs can have deleterious effects. Use by residential and visitor populations have increased on both spatial and temporal scales.

Tourism in Hawai'i has grown to nearly 7 million in 1999. The defacto population on any given day is approximately 165,000. With an average stay of 8.7 days, this equates to 58,360,690 visitor days a year. Repeat visitors make up 58% of the total number of people that arrived in our islands in 1999. The typical tourist has made 4 previous trips to Hawai'i. Hawai'i's 7 million visitors contributed over $11 billion to the state's economy in 1998 (Hawai'i Visitors Bureau 1999). The multiplier effect of tourist spending is responsible for over one-third of all personal income in the state (Hawai'i Visitors Bureau).

Over 1,000 ocean recreation companies exist to accommodate the 6 million tourists a year that use our marine resources. Over $800 million was generated from this industry in 1998 (Harrington 1999). The alluring attraction of oceans has created the potential for reef damage and destruction caused by human visitors who come to enjoy the unique beauty of the Hawaiian Islands.

Corals can serve as indicators of decline in the environment. They frequently occur in pristine areas and decline and eventually disappear as impacts are sustained. These indicators can be causally linked to human impacts. This can be extremely useful in monitoring anthropogenic impacts on reefs in attempts to predict the effects of disturbance (Keough and Quinn 1991). Connell's (1978) Intermediate Disturbance Hypothesis predicts higher species

diversity in regions with moderate impact, and low species diversity in high and low disturbance areas due to interference in successional patterns of recruitment.

Although trampling has been demonstrated to be a detriment to corals, breakage can also occur naturally and can be a viable means of reproduction for corals to horizontally expand their range (Maragos 1972, Dollar 1975, Birkeland et al. 1979, Highsmith et al. 1980 and Highsmith 1982, Hunter 1988, Cox 1992).

Liddle and Kay (1987) support the idea that corals developed and adapted to competing adaptive forces in habitats that originally did not include anthropogenic stresses. This led to size, morphology and skeletal limitations that determined the conditions they could be exposed to. They did not develop adaptive responses to withstand recent human interactions that result in breakage.

Two types of anthropogenic impact to corals, due to trampling can occur, chronic or acute disturbance. Corals may be subjected to prolonged perturbations, referred to as chronic events, or they may receive acute disturbance, which can be seasonal or of a temporary nature (Keough and Quinn 1991).

Direct human contact with corals can result in mortality, fracturing, tissue damage, decreases in gametic production and a reduction in growth (Woodland and Hooper 1977, Liddle and Kay 1987, Brosnan and Crumrine 1994, Brown and Taylor 1999,).

Studies of breakage of corals have generally concentrated on the impact of SCUBA diving. Damage has been documented worldwide, including reports

from French Polynesia (Tilmant, 1987), Australia (Rouphael and Inglis, 1995), and Hawai'i (Tabata, 1992).

Fewer studies have focused on the effects of trampling on corals due to activities of skin divers and waders. Trampling impacts have been assessed in Australia (Woodlawn and Hooper, 1977; Liddle and Kay, 1987), the Maldive Islands (Allison, 1996) and in Israel (Epstein et al., 1999).   Of the research conducted, only Harrington (1999), using qualitative methods, has reported on the effects of damage by skin divers and waders in Hawai'i.   Quantitative effects on coral damage by trampling in shallow water had yet to be determined for the Hawaiian Islands.

Sparse information is available on the impacts of skin divers and waders on corals. Information available is limited to areas in different parts of the world that are characterized by a high percent of fragile, highly branched corals (Woodland and Hooper 1977, Liddle and Kay 1987). Extensive damage was demonstrated at Australia's Heron Island to delicate *Acropora* species. A positive correlation was found between skin diving activity and broken coral in the Maldive Islands, where structurally fragile species dominate (Allison 1996).

 Although trampling has been associated with, and has been assumed to indicate environmental degradation, results from one regional study may not be applicable to predict damage in another area. Regional variations in species composition, climate and habitat diversity prevent large-scale spatial extrapolation. Yet, predictions can be made about similar geographic regions that contain relatively homogenous features. Species composition of Hawaiian

corals exhibit homogeneity throughout the state. Changing patterns of

recruitment and disturbance can be causally linked to the differences that do

exist. Variation in compositional differences between islands is small, although

structural differences are observable at the community level (Grigg 1983). Often

reefs in Hawai'i have been characterized by a single species of coral that

dominates the environment in a particular region (Gulko 1999). Species

composition of scelaractinian corals is remarkably uniform throughout the state of

Hawai'i, but there are great differences in relative abundance (Coral Reef

Assessment and Monitoring Program 2000).

In shallow, protected areas, disturbance directly attributed to skin divers

and waders is highly localized. Species morphology, branch arrangement and

skeletal strength may reduce the impact to some species of corals. Large or

encrusting forms found in high wave-energy environments are more resistant to

damage than branched or foliaceous forms that occur in calm water. Massive

and encrusting morphology and colonies with thick branches have the advantage

in being able to resist physical damage due to their growth form (Chamberlain

1978).

The highly branched, fragile acroporid corals are susceptible to breakage

from natural and anthropogenic forces. Hawaiian reefs differ from reefs

throughout the tropical Pacific in that the most dominant genera, *Acropora*, is not

found in the main Hawaiian Islands. Complex assemblages of *Acropora*

containing numerous species characterize many of the Indo-Pacific reefs. This

provides a highly rugose, habitat for a diversity of flora and fauna. Hawaiian

13

reefs lack this additional topographical relief provided by dense, highly branched forms and may not be as susceptible to trampling as some other areas. Corals exposed to trampling are subjected to both compressive and tensile forces. Resistance to breakage is variable under differing environmental conditions. The rates of breakage associated with anthropogenic forces are influenced by structural design and skeletal strength (Massel 1999). Properties of the skeleton that determine vulnerability to fracturing include colony size, morphology, branch geometry, density, porosity, bioerosion, composition, and strength (Wainwright et al. 1976, Chamberlain 1978, Vosburg 1982).

Studies have been conducted globally on the structural strength and porosity of mollusc shells and echinoderm spines (Taylor 1972, Currey 1975 and Massel 1999), industrial materials (Wainwright et al. 1976, Massel 1999), and reef corals (Wainwright 1963 and 1964, Buddemeier et al. 1974, Vosburg 1977 and 1982, Chamberlain 1978, Tunnicliffe 1982, Michell-Tapping 1983 and Bucher et al. 1998). No research had been conducted on skeletal strengths of Hawaiian coral species until this study.

This research integrates several facets of damage to corals by trampling: growth, mortality of colonies and fragments, and skeletal strength. Since human induced negative impacts are increasingly affecting coral reefs, research associated with this issue is vital in making sound management decisions regarding the future of coral reefs.

CHAPTER 2 COMMUNITY LEVEL TRANSPLANTATION EXPERIMENTS

2.1   INTRODUCTION

Coral reefs are the ocean's version of the tropical rainforest, containing some of the oldest and most biologically diverse ecosystems on earth. The Hawaiian archipelago is the most isolated in the world, with the closest continent lying more than 4000 km away and the nearest island group more than 1600 km. This geographic isolation has resulted in some unique characteristics of our coral reefs.

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positive correlation was found between skin diving activity and broken coral in the Maldive Islands, where structurally fragile species dominate (Allison 1996).

Although trampling has been associated with, and has been assumed to indicate environmental degradation, results from one regional study may not be applicable to predict damage in another area. Regional variations in species composition, climate and habitat diversity prevent large-scale spatial extrapolation. Yet, predictions can be made about similar geographic regions that contain relatively homogenous features. Species composition of Hawaiian corals exhibit homogeneity throughout the state. Changing patterns of recruitment and disturbance can be causally linked to the differences that do exist. Variation in compositional differences between islands is small, although structural differences are observable at the community level (Grigg 1983). Often reefs in Hawai'i have been characterized by a single species of coral that dominates the environment in a particular region (Gulko 1999).

In shallow, protected areas, disturbance directly attributed to skin divers and waders is highly localized. Species morphology, branch arrangement and skeletal strength may reduce the impact to some species of corals. Large or encrusting forms found in high wave-energy environments are more resistant to damage than branched or foliaceous forms that occur in calm water. Massive and encrusting morphology and colonies with thick branches have the advantage in being able to resist physical damage due to their growth form (Chamberlain 1978).

Data evaluating anthropogenic impacts is vital to properly manage these resources, yet research on these impacts is sparse. Quantitative research evaluating the physical and biological impacts of trampling in Hawaiʻi are almost non-existent. Harrington (1999) provides a qualitative assessment of damage to corals at Kahaluʻu on the Island of Hawaiʻi.

With the complexity of coastal marine ecosystems and spatial and temporal variation, it is extremely difficult to isolate specific impacts. This study is designed to quantitatively address the impacts to corals by skin divers. Three main investigations strengthen the experimental design.

4) Community level studies evaluate linear growth rates and mortality, determined through coral transplantation into sites that range along a gradient of human use (this chapter).

5) Colony level experiments control for all factors affecting growth and mortality. Simulated trampling was conducted under experimental conditions to determine the rates of growth, mortality, and recovery of dominant Hawaiian corals subjected to trampling damage (see Chapter 4).

6) Skeletal strength and breakage rates were also quantified under laboratory controlled conditions (see Chapter 5).

Community level studies (1) were linked to controlled colony level experiments (2) to establish the causal relationship between coral growth and mortality and impact from trampling. Laboratory breakage tests (3) confirmed rates of fragmentation during field experiments, with species strength remaining consistent throughout all investigations.

Corals have been used as bioindicators of ecological decline. They may indicate broader effects in coral community changes directly related to anthropogenic impact. Different parameters have been used to assess anthropogenic impacts on corals, including species richness (S), diversity (H'), and evenness.

Coral transplantation has successfully been used in manipulative experimentation to compare spatial differences. Transplantation experiments can evaluate growth differences between disturbed and pristine environments. Comparative measures of disturbances in different habitats can be obtained through transplantation and growth measurements. For example, Te (2000) compared growth rates of corals transplanted into different sediment regimes. To accurately determine growth rates from transplanted corals, the experimental design must allow sufficient time for measurable growth. A one-year period was demonstrated to be sufficient in addressing this issue (UNESCO 1987, Te 2000).

Coral growth rate is a relevant parameter for determining environmental decline on reefs. Although within and between species growth rates can be variable in corals, one of the best quantitative measures to determine stress due to disturbance is growth (Birkeland et al. 1976). This biological parameter integrates several physiologic processes. Growth measurements can provide a quantifiable measure of the extent of an impact by determining the relationships between gradients of anthropogenic impacts and ecological distribution (Keogh and Quinn 1991).

Alizarin red staining has been successfully used to determine differences in growth of corals (Brown et al. 1985). This method uses a biological stain that is incorporated into the tissues of the coral to leave a permanent marker that is evident in the skeleton.

2.2   <u>Study Sites</u>

Three sites were evaluated, representing a gradient that ranged from low to high human use by skin divers and waders. All sites selected have been designated as areas of concern by the State of Hawaii, Department of Land and Natural Resources' Division of Aquatic Resources. To differentiate between induced and natural damage, a control group was established. Each site included a control station with similar physical, chemical and biological characteristics. Human use was quantified at each site. Primary site selection rationale was based on the following criteria.

- Degree of use by skin divers and waders to encompass a full range of use, from sites receiving low impact to sites with high impact.

- Availability of appropriate control stations.

- Availability of human use data and/or reasonable access to sites.

Kāneʻohe Bay

Kāneʻohe Bay is located on the northeast coast on the island of Oʻahu. It is the largest embayment in the State of Hawaiʻi and the most extensively

studied. It covers an area of 5,670 ha (Hunter 1993). Two navigable channels

penetrate the outer barrier reef, at the northern and southern ends of the bay.

The inshore, inner bay and outer bay comprise the major physiographic

zones of Kāneʻohe Bay. The inshore zone is composed of the shoreline intertidal

zone and the fringing reef. The inner bay consists of patch reefs separated by a

sediment bottom lagoon and an inner fringing reef. The lagoon is divided into

three sectors: South Bay, Central Bay and North Bay. The outer bay zone

contains the barrier reef (Smith et al. 1973) (Figure 2.1).

Anthropogenic influences affecting Kāneʻohe Bay include erosional runoff

of terrigenous sediments, diversion and channelization of streams, changes in

the watershed and riparian environments, recreational use, and 25 years of

sewage effluent discharge (Laws and Allen 1996). Diversion of sewage outfalls

began in 1977, with the final point-source discharge eliminated by 1986.

Substantial decreases in turbidity and nutrient concentration occurred as a direct

result of sewage abatement. A corresponding shift in benthic community

structure and a decrease in phytoplankton abundance resulted (Hunter and

Evans 1995, Laws and Allen 1996). Despite a population increase in the

surrounding watershed, and expansion of commercial and recreational use, the

water quality of Kāneʻohe Bay improved following sewage diversion, from highly

eutrophic to relatively oligotrophic conditions (Laws and Allen 1996).

Water conditions within the bay range from estuarine to oceanic. Nine

perennial streams drain into the bay from the surrounding watershed and have a

major influence on water quality. Stream runoff is highly variable and ephemeral.

Due to the extensive shallow reef habitat freshwater mixes slowly with inshore water (Jokiel et al. 1991).

Three reef types are found in Kāneʻohe Bay: fringing reefs, patch reefs and the barrier reef. The tops of the fringing reefs are generally in water less than 1 m in depth. The reefs occur in calm waters along the shoreline. Seventy-nine patch reefs are located within Kāneʻohe Bay. They are concentrated near the channels, and range from 21 to 850 m in diameter. The upper slopes of these patch reefs display the highest percentage of coral cover (Jokiel et al. 1991).

Low Impact Site

The medium and low impact sites are located within Kāneʻohe Bay. Patch reef #39, located in the North Bay is visited daily except Sundays and federal holidays by 2 small commercial operators. This size of this patch reef encompasses 17,068 square meters (Hunter 1993). This site represents an area of low impact with < 5,000 users per year (Figure 2.1).
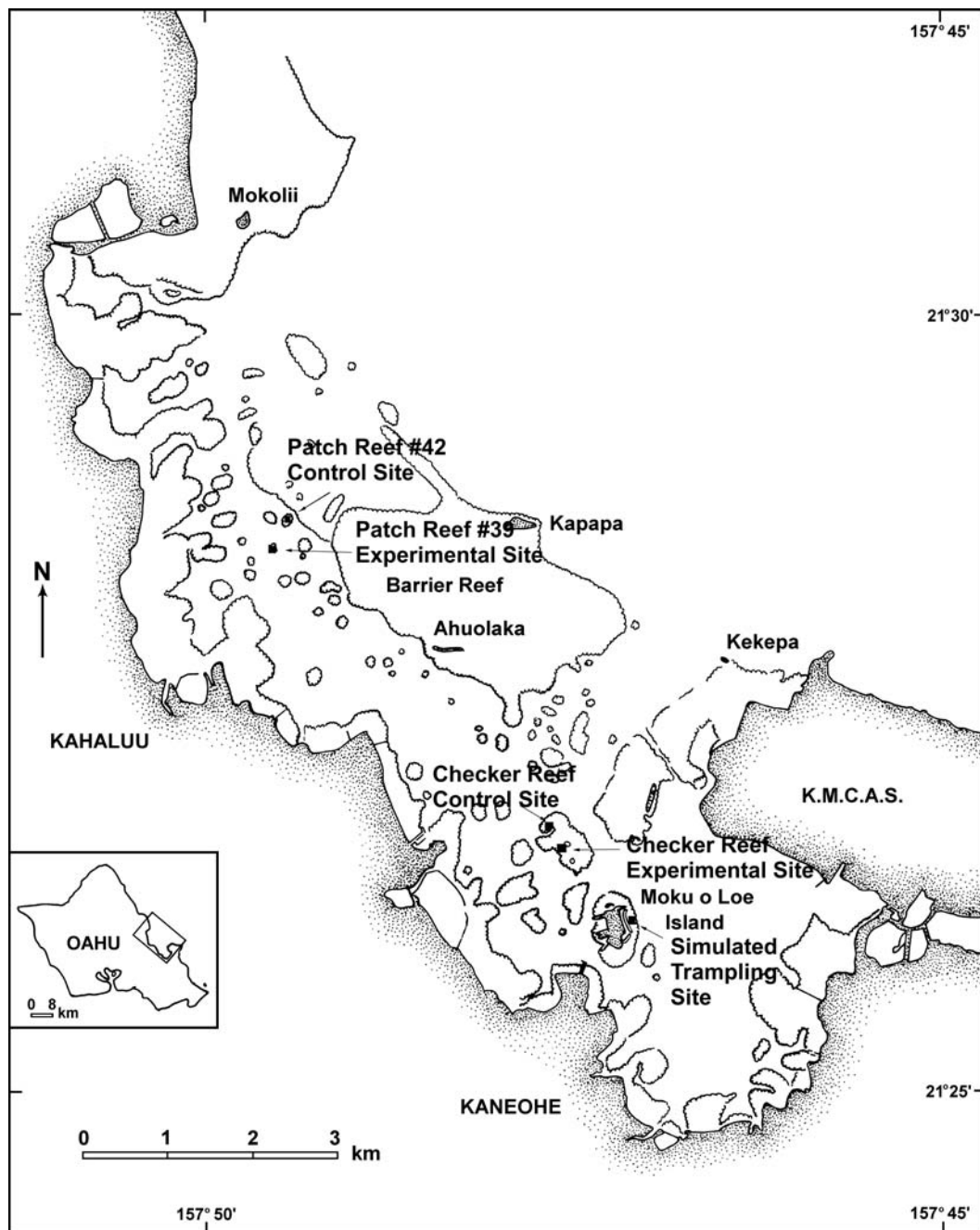
Figure 2.1 Coral Transplantation Sites in

Kāneʻohe Bay, Oʻahu, Hawaiʻi

The adjacent patch reef #42 serving as the control station, has no commercial activities and receives minimal recreational use by residents. This reef is slightly larger than patch reef #39, covering 24,008 square meters. These stations were selected to represent low impact by skin divers and waders. Quantification of human use at these sites was established through frequent direct counts of visitors (Figure 2.1).

Medium Impact Site

Patch reef #8, more commonly known as Checker Reef, is located in the Central Bay and used on a daily basis except Sundays and federal holidays by a large commercial operator. This is by far the largest patch reef within Kāneʻohe Bay, covering 320,841 square meters. This area was selected as the medium impact, experimental station. Approximately 50,000 people visit this site annually. Activity is confined to the leeward, south side of the reef (Figure 2.1).

The windward, north side of the reef receives no commercial visitors and minimal local use. This was designated as the associated control station (Figure 2.1).

Kahaluʻu Beach Park - Island of Hawaiʻi

Kahaluʻu Beach Park is located on the west coast of the Island of Hawaiʻi. The Division of Aquatic Resources lists this site as part of a fisheries replenishment area (FRA), where aquarium fish collecting is prohibited (Figure 2.2).
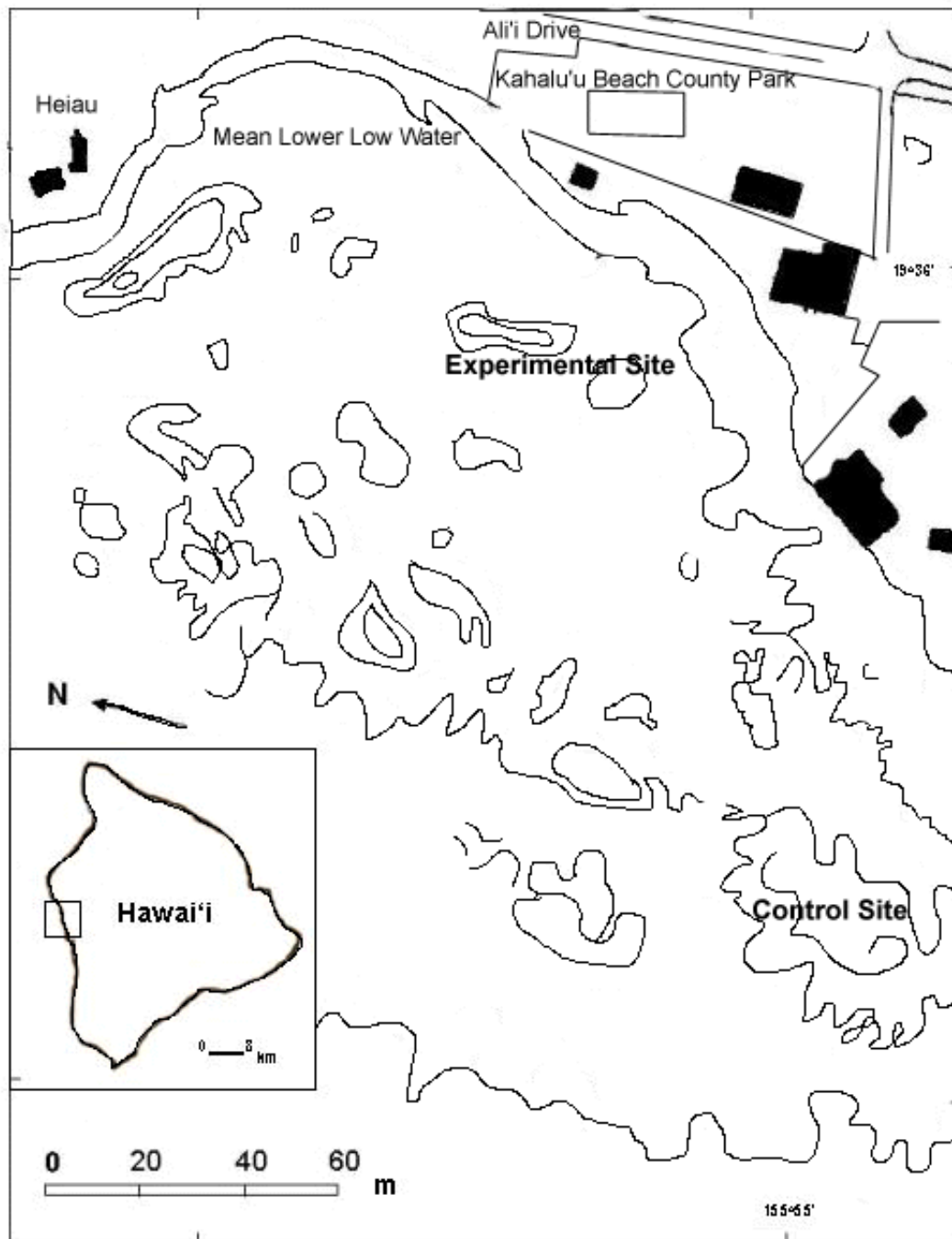
Figure 2.2 Coral Transplantation Sites in Kahalu'u Bay,

Island of Hawai'i

It once supported a large pre-contact population of Hawaiians. Archeological surveys have revealed house sites, *heiau*, and petroglyphs located near the bay. A salient feature within the bay is known as Pāokamenehune or menehune wall, a large breakwater that once enclosed Kahaluʻu Bay and Kealialia, the tidal lagoon on the makai side of the beach park. Many of the large boulders that once formed the 1,189 meter long structure have been scattered by storm surf over the years. Kahaluʻu officially became a beach park in 1953, when the County of Hawaiʻi obtained the lease and eventually the deed from the Bishop Estate. This beach park is one of the most popular skin diving beaches on the Big Island, accommodating over 350,000 visitors a year according to County lifeguard data from 1998. Visitors staying at the Keahou Beach Hotel, adjacent to Kahaluʻu Beach Park, frequent the area. Swimming, diving, and fishing are also common here within the protected waters of the fringing reef. Surfing is a popular activity just outside the bay. Although the skin diving area is estimated at between 5 and 6 acres, most activity occurs in a relatively small, shallow area. During periods of strong surf a powerful current runs north from Kuʻemanu Heiau along the rocky shoreline and continues out to deeper waters where it eventually dissipates. More rescues are made here by lifeguard and fire rescue personnel than at any other beach on the West Hawaiʻi coastline (Clark 1983).

High Impact Site

The high impact station is heavily used by tourists and residents alike with the main activities being skin diving and wading (Figure 2.2). This area is easily accessible.

The associated control station is located on the south side of the bay in an area where minimal activity occurs. This section of the bay has limited human use due to difficult accessibility (Figure 2.2).

Porites compressa (finger coral) and *Pocillopora meandrina* (cauliflower or rose coral) were selected for transplantation. Species selection was based on the following criteria.

- Natural occurrence at all sites of transplantation.

- Physical morphology.

- Domination at many of the other areas of concern throughout Hawaii.

Site comparisons-Physical and Chemical Parameters

To assess similarity between experimental and control stations and to control for other factors that affect coral growth and mortality, physical, chemical and biological parameters were measured. The measurement of different community parameters provided a multivariate description of the communities, to address the environmental variables influencing corals.

Temperature

Scleractinian or reef-building corals are geographically restricted by temperature to tropical regions. Lethal and sub-lethal effects can result from temperatures below or above the thermal limits for corals. Physiological responses to elevated temperatures include bleaching, a reduction in calcification and growth, a decrease in net productivity, increased respiration rates, changes in reproduction and increased mortality (Jokiel and Coles 1990).

Single celled, symbiotic algae live within the coral tissues. These zooxanthellae photosynthesize to produce nutrients for the corals. Under thermal stress, corals will expel their zooxanthellae and begin to bleach. Corals live close to their lethal temperature limits during the summer. Jokiel and Coles (1990) demonstrated that temperature elevations of only 1^oC to 2^oC above summer ambient temperatures for several weeks can induce bleaching in some species. Exposure to 3^oC to 4^oC rise above ambient, can cause rapid bleaching in as little as 1 to 2 days.

Field and laboratory experiments on growth indicate that an increase of only 1^oC to 2^oC above summer maximums will reduce skeletal accretion and linear extension rates in corals (Coles and Jokiel 1978, Hudson 1981).

Elevated temperatures result in a decrease in net productivity with lowered carbon fixation rates. An inverse relationship was observed between photosynthesis to respiration ratios and temperature. As temperatures increased above summer ambient temperatures, the photosynthesis to respiration ratio decreased.

Temperature rise, increasing respiration rates, can result in a reduction in autotrophic capacity. A correlation between high temperature and respiration rates exists, evidenced by the coral species with the highest respiration rates being the most susceptible to bleaching and mortality (Coles and Jokiel 1977).

Temperature variations can also affect coral reproduction and recruitment. Elevated temperature can stimulate release of immature planula that exhibit higher mortality rates. Recruitment success is also temperature dependent. Success of recruits were inhibited at temperatures below the normal threshold, while enhanced settlement rates have been reported at temperatures higher than ambient (Jokiel and Guinther 1978, Coles 1985).

Salinity

Lethal and sub-lethal effects can result from salinity stress in corals. Decreases in growth, reproduction, survivorship, respiration and photosynthetic rates have all been reported (Muthiga and Szmant 1987, Coles and Jokiel 1992, Moberg et al. 1997, Ferrier-Pages et al. 1999).

Salinity tolerances for corals can range from as low as $25^o/_{oo}$ to as high as $45^o/_{oo}$. Most coral reefs in Hawai'i have a much narrower salinity range. Since corals can not osmoregulate, stress can occur from salinities that deviate from ambient. Experimental investigations suggest that salinity tolerance of most reef corals is within $5^o/_{oo}$ of ambient salinities. Prolonged variations from this range will result in mortality of corals.

Hawaiian corals were found to be more sensitive to elevated salinities than to lowered salinities (Edmonson 1928). Of the genus tested, *Pocillopora* was the least tolerant to variations in salinity.

Reduced photosynthesis and respiration rates resulted from small changes in salinity in *Stylophora pistillata* in France (Ferrier et al. 1999) and *Porites lutea* and *Pocillopora damicornis* in Thailand (Moberg et al. 1997). Chlorophyll content declined after salinity variations of only $7^o/_{oo}$ (Muthiga and Szmant 1987).

Turbidity

The distribution of reef-building corals is limited by sunlight. Zooxanthellae, the dinoflagellate symbiont, living within coral tissues, must photosynthesize to produce nutrients essential to coral survival. Depth and turbidity are directly related to light levels reaching the benthos, where corals reside. Corals living in shallow waters are less influenced by turbidity than deeper water corals. Turbidity affects water visibility due to the presence of suspenoids (Kirk 1985). These suspended particles reduce light levels with a subsequent reduction in photosynthesis, calcification rates, lower energy production and slower growth rates (Falkowski et al. 1990, Rogers 1990, Miller and Cruise 1995). Te (2000) found lower oxygen rates in *Pocillopora damicornis* with increasing levels of turbidity. Significant decreases in growth and survival of corals with increases in turbidity in the South Bay of Kāneʻohe Bay were reported by Coles and Ruddy (1995).

30

Besides a reduction in light availability, direct settlement of suspended solids can negatively affect corals. Energy resources are redirected away from reproduction and growth to mucous production and other physiological responses for removal of particles (Lasker 1980). Sedimentation can result in lower coral cover and diversity, increases in branching morphologies, lower growth rates, reduced recruitment, decreases in net productivity, retarded rates of accretion, and higher mortality rates (Rogers 1990).

Water Motion

Water motion acts as a mechanism for the delivery of nutrients to corals and other benthic organisms, influencing their growth rates. Water motion can also affect recruitment, morphology, composition and distribution of corals (Jokiel and Morrissey 1993). Rates of water motion explained up to 98% of the variability in growth rates of the alga *Kappaphycus* in Kāneʻohe Bay (Glenn and Doty 1992).

Synergistic effects

Environmental tolerances to independent factors are easier to determine than combined effects. Yet, physical, chemical, and biological factors can interact to produce synergistic effects that affect growth and mortality in corals. For example, bleaching can result from a lack of light (Yonge and Nichols 1931), variations in temperature (Jokiel and Coles 1977), or salinity (Egana and DiSalvo 1982). Temperature tolerances in *Montipora capitata* were reported to be

affected by salinity and light (Coles and Jokiel 1978). Interactions between dissolved oxygen levels, water motion, sedimentation, and other variables may be just as important to the physical state of corals as temperature, salinity and light.

Site Comparisons-Biological Parameters

Biological factors often used to characterize reefs include abundance, diversity and composition of coral and fish populations. Yet, experimental and control stations may exhibit differences due to disturbance. Diversity and biomass of the community change in impacted areas. Various anthropogenic activity can depress local populations or drive them to extinction (Keough and Quinn 1991). Decline in the number of species or distribution of species abundance becomes uneven.

The Intermediate Disturbance Hypothesis, first described by Connell (1978), argues that disturbances may help provide diversity by interfering with successional patterns. Without disturbance, an area is often inhabited by a few dominant species. This is also true of regions with intense disturbance that keeps species diversity low. An intermediate stage may exist where recovery from disturbance may be related to an increase in species richness. These regions are colonized by both early and late successional species. Competition between species will later exclude some species. This model is most applicable to repeated acute disturbances as in seasonal tourist impacts or low to medium

impact areas. Chronic disturbances maintained over long periods such as those sustained in trampling damage do not favor increased diversity.

2.3   APPROACH AND METHODS

In situ-Community level studies

The ability to detect a change in community parameters is affected by the number of samples, the difference between means, and the variation. To assure sufficient power, appropriate sample size was calculated using an analysis of variance (ANOVA). This power analysis was conducted to determine whether this experimental design was likely to detect a difference in growth between corals at experimental and control stations. The sample size necessary to detect an effect, if one does exist, is 7 colonies. This was based on values from transplantation experiments conducted on growth by Te (2000) in Kāneʻohe Bay. Ten colonies of each species were transplanted in this experiment to allow for loss.

Ten colonies of *Porites compressa* (finger coral) and 10 colonies of *Pocillopora meandrina* (cauliflower or rose coral) were selected from the general vicinity of each site. Colonies were split in half. This procedure eliminates differences in genetic diversity and maximizes the statistical power of the sampling regime. Corals were stained with Alizirin red for an 8-hour period. Stress bands have been reported in the skeletons of corals left over 12 hours in the dye (Hudson 1981, Dodge et al. 1984). This biological stain is incorporated

into the tissues of the coral and a permanent marker is evident in the skeleton. Alizarin powder was dissolved in a small amount of seawater and diffused in 880 liters of seawater in 2 tanks at the laboratory at the Hawai'i Institute of Marine Biology (116.5 x 116.5 x 65 cm) for the corals at the nearby Kāne'ohe Bay sites. Identical concentrations were used at Kahalu'u Beach Park in 4 tubs (1m x 45cm x 45cm) under field conditions. Alizarin concentration of 15 parts per million was used. Concentrations of alizarin below 20 ppm are not deleterious to corals. Aeration of the corals in solution was supplied by airline in the lab and battery operated aquarium pumps in the field.

Half of each colony was transplanted into the experimental impact station; the other half was placed in the unimpacted control station. Corals were inconspicuously identified and secured with wire to short unobtrusive markers or attached to natural areas in the reef with plastic cable ties. The corals remained in the field for a period of 11 months. This is sufficient time to encompass seasonal variations in growth and to allow time for measurable growth. Linear extension was evaluated by measuring the distance between the permanent pink marker band incorporated through staining and the outer most portion of the skeleton. Paired comparisons provided an index for impact based on the level of impact at each station.

Site Comparisons

The measurement of different community parameters provided a multivariate description of the communities at the impact and control stations to

34

address the environmental variables affecting growth and mortality of corals. A one-way analysis of variance compared physical conditions between stations.

Physical and Chemical Parameters

A mean of 3 measurements was used from 3 independent collection periods for all physical and chemical parameters over the 11-month period corals remained in the field. Other water quality parameters were not measured since it had previously been established that water column characteristics are remarkably similar in all sectors of Kāneʻohe Bay (Laws and Allen 1996).

Temperature

Temperature was recorded with the use of an Onset HOBO H8 temperature data logger enclosed in a waterproof case. One-hour selected sampling intervals were designated for the 1-year data collection period that corals remained in the field. Measurement specifications include accuracy of $\pm 0.7^{o}$ C, a temperature range of -20° C to $+70^{o}$ C, and time accuracy of ± 1 min./wk. at $+20^{o}$ C. Temperature loggers were deployed at patch reef 42 in the north sector of Kāneʻohe Bay and in Kahaluʻu Bay. Data from the Hawaiʻi Institute of Marine Biology's weather station located on Moku o Loʻe, were used to track temperatures at the adjacent Checker Reef site. Data loggers were installed to track deviations from ambient temperatures that may affect coral growth. Since experimental and control stations at all sites were located in close

proximity to one another, temperature differences between stations were not relevant.

Salinity

Salinity was determined with the use of a refractometer to determine differences between experimental and control stations.

Visibility

Visibility was determined using 2 widely established methods, total suspended solids (TSS) and secchi disk distances.

Horizontal secchi disk distance measurements were made using a standard 30cm diameter white disk attached to a 50m transect line.

Two-liter sampling bottles were used to collect subsurface water for determination of TSS. Samples were filtered through a millipore manifold and suspended solids were collected onto preweighed glass microfiber Whatman GF/C filters. Filters were then thoroughly dried and TSS determined through weighing of particulate matter.

Water Motion

Plaster of paris clod cards were used to compare water motion between impact and control stations using the method described in Jokiel and Morrisey (1993).

'Clod cards' were prepared using 50g of calcium sulfate (plaster of paris) per 45g of water. The well-mixed slurry was poured into polyethylene ice-cube trays. Air bubbles were removed by tapping on the trays. Remaining liquid was decanted from the surface of the hardening clods. Following removal from trays, clods were air dried for a period of 2 weeks. Subsequent to drying, clods were sanded to obtain uniform weights within 2g of each other. Contact cement secured clods to 5x8 cm thin, white, plastic board. Dry weights and site identifications were recorded directly on the cards using pencil. Two replicate clod cards were secured with rubber bands to a masonry brick and placed at each station for a 24-hour period. This was repeated on 3 occasions. Clods were rinsed in fresh water, then thoroughly air dried for a three-week period. An average weight was obtained for each station to allow for effects of humidity. A 20-liter calibration container was used for diffusion of control clod cards to represent a motionless environment. The diffusion factor was estimated from the enhanced dissolution rate of clod cards in moving water at each station, compared to the dissolution rate of control cards in motionless water of equal salinity. A diffusion index factor (DF) was obtained by dividing the still water calibration value by the weight loss during field exposure. A one-way analysis of variance (ANOVA) was used to determine significant differences between experimental and control stations.

'Clod cards' are an accurate, quantitative measure that has been widely used in marine habitats, to correlate growth rates with water motion and to compare water movement between sites. Gypsum based plaster of paris 'clod

cards' or 'Muus balls', have become a widely accepted quantitative method for comparing water motion regimes in the field to determine physical-biological interaction. These calcium sulfate blocks provide a simple, inexpensive technique with diverse applications. This method has been used to evaluate current velocity, flow intensity, waves, energy dissipation rates, spatial patterns of dissolution, circulation patterns, turbulence intensity, mass transfer and flow comparisons.

McConnel and Siegler (1959) first introduced the concept of using the dissolution rate of a solid material to provide an index of water movement. Sodium chloride tablets were used to determine the speed of currents in streams. The gypsum dissolution method was first introduced by Muus in 1968 to measure water flow. Doty (1971) subsequently employed this method to relate water motion to macroalgal growth rates. Jokiel and Morrissey (1993) and Thompson and Glenn (1994) investigated the effects of temperature, salinity and water volume on rates of dissolution.

Jokiel and Morrissey (1993) found that if 'clod cards' were eroded beyond their linear range, they were no longer an integrative measure of water motion. Relatively constant weight loss is maintained until the total weight of the gypsum is below 30% of the original weight.

By dividing the weight loss of 'clod cards' in the field by the weight loss of control cards in motionless water of equal salinity and temperature, a diffusion index factor (DF) can be determined (Doty 1971).   Use of these still water calibrations have been shown to be variable (Muus 1968, Doty 1971).

38

Temperature and salinity can influence weight loss in clod cards. Variability can also be attributed to the small water volume in calibration containers. Jokiel and Morrisey (1993) demonstrated little change in the weight loss of clods with increasing volume after 20 liters. This is the minimum volume necessary to represent weight loss in still water for a 50g clod card.

Another cause of variability in weight loss is the placement of clods near the bottom of containers. Dissolution is prevented once the solute from the clod has saturated the water. The diffuse boundary layer close to the bottom may have less of a concentration gradient, resulting in a lower dissolution rate (Thompson and Glenn 1994).

Several recommendations have been suggested to alleviate these problems. Adjusting placement of clods away from the bottom (Thompson and Glenn 1994), perforation for water exchange and increased water volume in calibration containers (Jokiel and Morrissey 1993) and discontinuation of the diffusion index calibration method (Thompson and Glenn 1994, Porter et al. 2000) have all been employed successfully.

In evaluating dissolution rates, Porter et al. (2000) found the clod card method ineffective in steady flow measurements and fluctuation intensity in environments of mixed flow. Although flow meters are needed to measure absolute velocities of water motion, relative rates can be accurately evaluated using the 'clod card' method. Clod cards were used in this study for relative comparisons of water motion between experimental and control stations, to

control for factors that affect coral growth and mortality providing similar environments for transplanted corals.

Biological Parameters

Numerous ecological sampling methods have been designed and employed by biologists to survey nearshore environments. Replicate samples can provide accurate estimates of species composition and abundance. Although transects may vary, when pooled, they offer a representation of the community as a whole.

The sampling regime selected in this study is an effective design to measure relative density. The populations at the experimental stations relative to the populations at the control stations were addressed using percent cover estimates and fixed width strip transects.

Fishes

Fixed width strip transecting is the most widely used method to visually survey fishes. This method can provide data on fish abundance, density, species presence and biomass. In this study, visual transects compared abundance, and diversity of fishes at each site. Three 50m transects were used to survey a four meter corridor encompassing a total sampling area of $600m^2$. Observer variation was controlled by using the same surveyor at each site, to sample both the experimental station and its associated control station, to determine relative

differences in fish populations. Observations for each site were conducted on the same day, within a few hours of each other, to control for temporal variations.

Benthos

The percent cover estimate method was used to determine percent cover and diversity (H') of coral, algae, and non-biological substrate at each station. A 1m^2 PVC quadrat was placed at 25 randomly selected points along each of three 50m replicate transects to determine percent cover and diversity (H') of coral, algae and non-biological substrate at each station. An estimate of the percentage of quadrat area occupied by each taxon was made. The 1m^2 quadrat was partitioned into 100 equal subunits, with percent cover being independently estimated for each subunit. Smaller subunits improve accuracy and make it less difficult to estimate percent cover of organisms within the quadrat.

Another commonly used method for surveying biological substrate is the quadrat intersect method. This method records the taxon under each intersection. Parallax problems are eliminated when 2 sets of strings lineup, with one on top of the other, to indicate the observer's position. This method can provide an estimate of the abundance of benthic organisms but not of diversity.

The primary advantage of the percent cover estimate method is that it provides an estimate from which the area of benthos covered by each organism can be derived. Diversity can be calculated using this method, unlike the quadrat intersect method which does not include the entire quadrat and may miss under represented species used in determining diversity. Another advantage is that

41

rare or cryptic species are less frequently omitted. Principle disadvantages include observer error and bias. This temporally intensive method also limits the number of replicates possible on a dive.

2.4   RESULTS

Survivorship

The effects of trampling caused statistically significant reductions in the number of surviving transplanted colonies. Survivorship differed significantly between experimental and control groups at all three sites.

The magnitude of decline was astounding and the progression of mortality was rapid at the high impact site. None of the 20 colonies at the experimental station remained attached after an 11-month period (Figure 2.3).

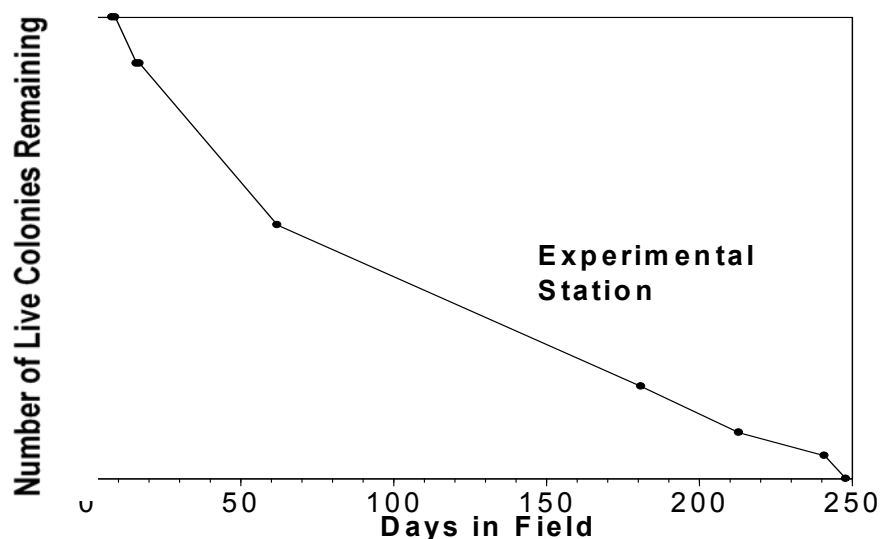Two dead, unattached partial colonies were recovered. Sixteen live

Figure 2.3 Coral Decline at Kahaluʻu Beach Park

colonies were recovered from the control station at the high impact site.

42

A definite pattern of decline emerged along the gradient of impact. While survivorship in the control group remained high, colonies exposed to the effect of trampling declined. Survivorship dropped from 70% at the low impact site to 55% at the medium impact site. Further decline was reported from the high impact site, with 0% of the transplanted colonies surviving (Figure 2.4).
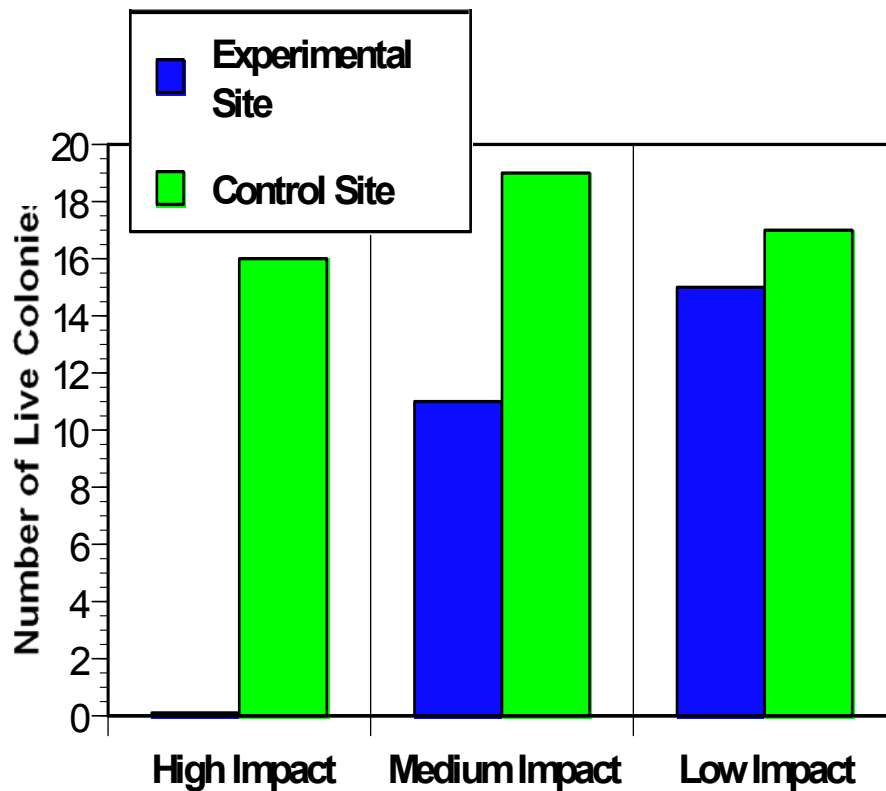

Figure 2.4 Survivorship along a Gradient of Human Use

<u>**Growth**</u>

Paired comparisons showed no significant difference in mean linear extension rates at either the low or medium impact sites (Figure 2.5).
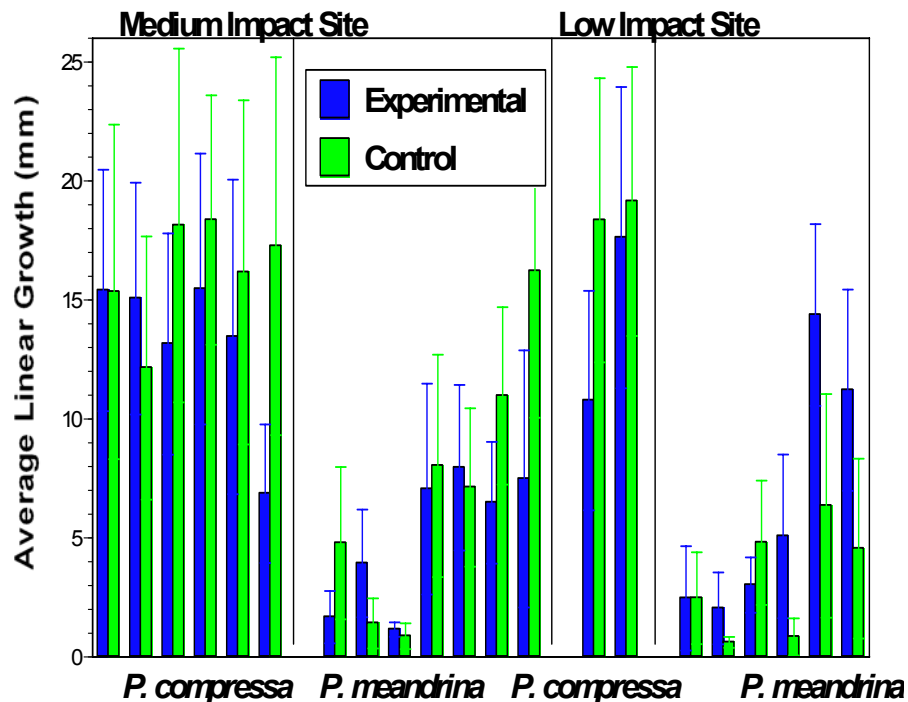
Figure 2.5 Paired Comparisons of Coral Growth

No growth comparisons were made for the high impact site, since no transplanted colonies remained at the experimental station. Average linear growth was established for the control group.

Growth rates at the low impact site for *Porites compressa* averaged 16.2mm in the experimental group and 17.9mm in the control group. Slightly lower growth was reported for the medium impact site. Colonies averaged 13.8mm and 15.7mm for the experimental and control stations respectively, over the 11-month experimental period. Mean growth rates for the same time period

44

in the control group at the high impact site was 10.3mm. No comparison was made with experimental colonies due to 100% mortality.

Mean growth measurements for *Pocillopora meandrina* were significantly lower than those for *Porites compressa*. Growth at the low impact site for this species, deviated from all the other sites, demonstrating higher linear extension rates at the experimental station. Colony growth averaged 6.4mm for the experimental transplants and 3.5mm for the control colonies. Growth at the medium impact site averaged 5.1mm in the experimental group and 6.9mm in the control group. At the high impact site, mean values for *P. meandrina* were 4.3mm in the control group. No comparison could be made relative to the experimental group. No statistical differences in linear growth between experimental and control colonies were detected (Figure 2.6).
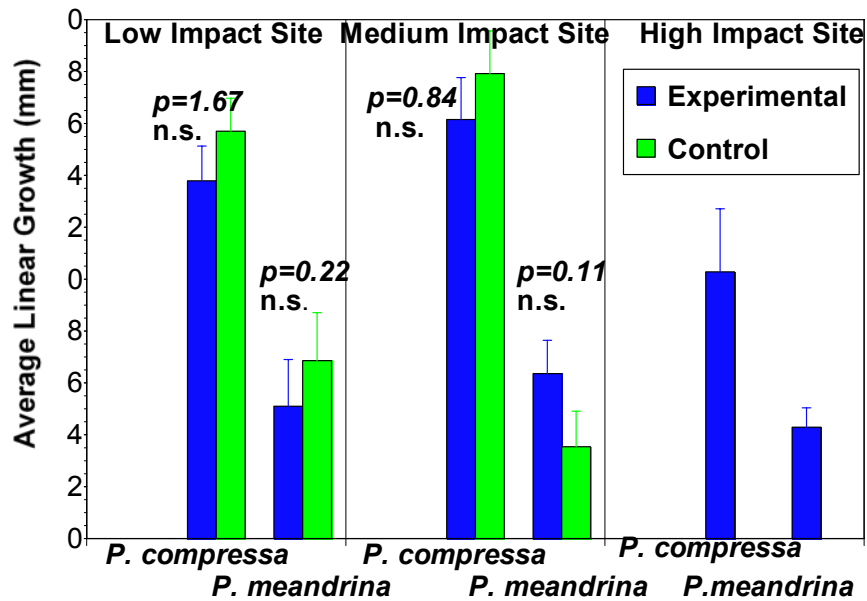
Figure 2.6 Average Linear Growth at Sites

Site Comparisons

Physical and Chemical Parameters

Temperature

Temperature data loggers placed at the high and low use sites and the Hawai'i Institute of Marine Biology's weather station located near the medium use site did not detect temperatures that exceeded the thermal limits of corals. Although summer ambient temperatures were surpassed on several occasions at the high and low use sites, the maximum duration of elevated temperature was only 11 hours. Decreased growth rates and increased mortality are not expected to occur in less than 1-2 days for elevations of $3^{o}C$ to $4^{o}C$ above

summer ambient temperatures and several weeks at elevations within the 1^oC to 2^oC range (Coles and Jokiel 1978).

Salinity

Salinity at all 3 sites was not significantly different between experimental and control stations.

Visibility

Turbidity was very low at all sites (Table 2.1, Figure 2.7).

Site	Diffusion Increase Factor (DF)	Total Suspended Solids (TSS) (mg/l^{-1})	Seccchi Distance (m)	Mean Coral cover (%)	Non-biological substrate (%)
High Impact site (Kahaluʻu)					
Experimental station	12.5 ± 2.8	6.9 ± 2.3	4.5 ± 2.6	1.6 ± 0.1	90.0 ± 0.4
Control station	10.4 ± 3.3	7.3 ± 0.2	14.7 ± 3.0	34.1 ± 8.9	60.0 ± 8.5
Medium impact site (Checker Reef)					
Experimental station	13.4 ± 2.4	8.6 ± 4.8	6.6 ± 0.1	13.8 ± 0.6	69.8 ± 0.3
Control station	16.2 ± 2.5	8.0 ± 4.8	6.8 ± 0.6	25.5 ± 9.6	46.5 ± 5.3
Low impact site (patch reefs 39/42)					
Experimental station	15.6 ± 2.1	5.2 ± 4.1	13.9 ± 3.1	76.5 ± 20.0	17.4 ± 17.0
Control station	10.8 ± 2.3	6.1 ± 4.0	10.3 ± 0.5	89.3 ± 6.7	4.6 ± 2.1

Table 2.1 Summary of Mean Values for Physical, Chemical and Biological Parameters
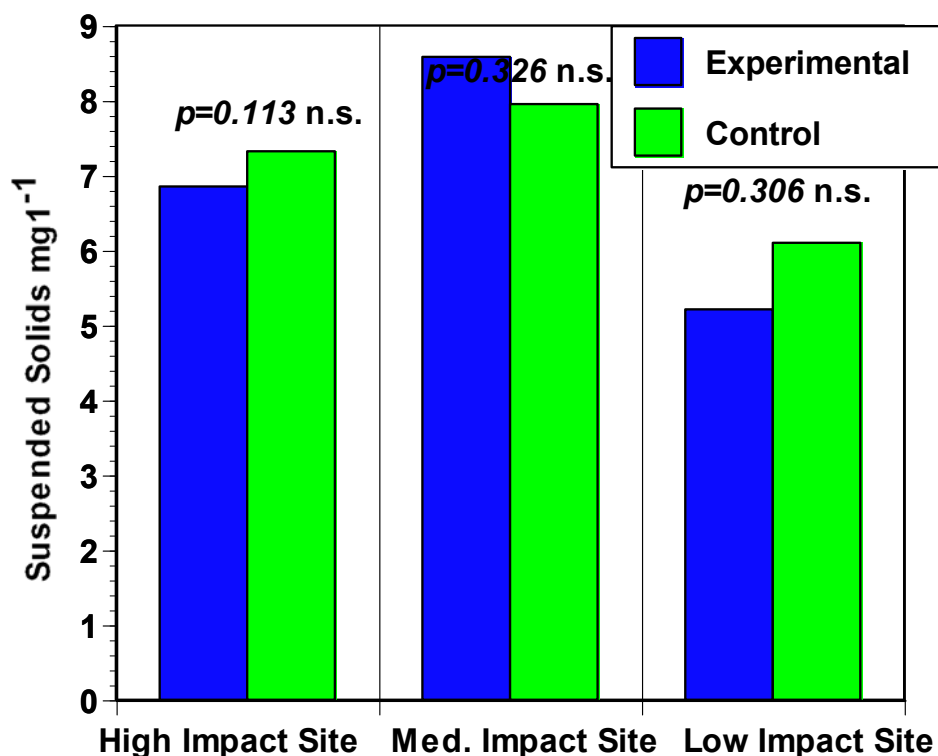
Figure 2.7 Site Comparison of Total Suspended Solids

Total suspended solids (TSS) ranged from 5.2 to 8.6 mg l^{-1}. No statistical differences were found between experimental and control stations at the high impact site (p=0.113, α=0.05), medium impact site (p=0.326, α=0.05), and low impact site (p=0.306, α=0.05). Suspended particulate at the high impact site averaged 6.9 and 7.3 mg l^{-1} for the experimental and the control stations respectively. At the medium impact site, TSS at the experimental station averaged 8.6 mg l^{-1} and 8.0 mg l^{-1} at the control station. As expected, particulate matter was the lowest at the low impact site, with mean values of 5.2 mg l^{-1} at the experimental station and 6.1 mg l^{-1} at the control station.

Mean secchi distance measurements of 4.5m and 14.7m demonstrated a significant difference between the experimental and control stations at the high impact site. Measurements at other sites were not statistically different.

Water Motion

There was a statistically significant difference in mean diffusion factors between the experimental and control stations at the medium and low use sites (Figure 2.8).
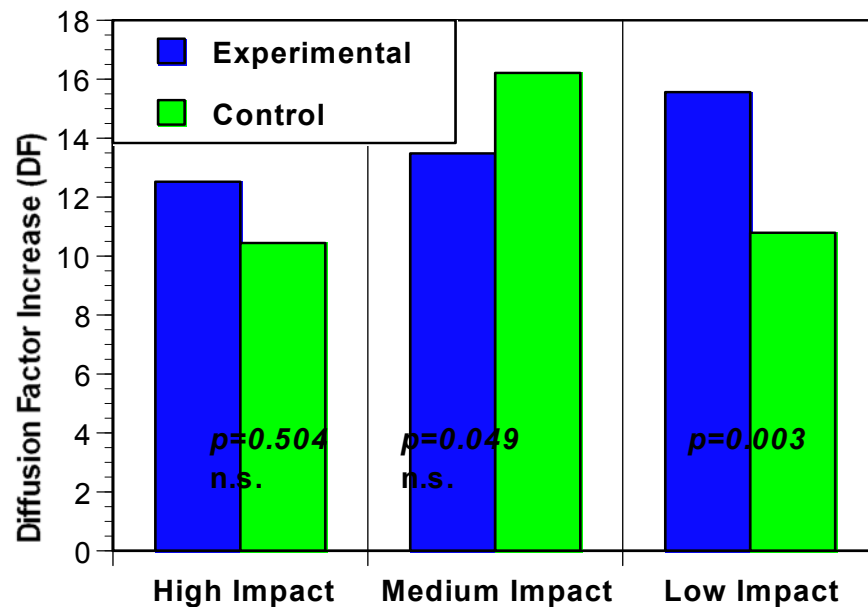

Figure 2. 8 Site Comparisons of Water Motion

The medium impact site showed 20% lower water motion at the experimental station relative to the control station (correlation coefficient=0.049, α=0.05). The low impact site exhibited the opposite with slightly higher water motion (6%) at the experimental station (correlation coefficient=0.003, α=0.05).

Results revealed no significant difference in water motion between the experimental station and the control station at the high impact site (correlation coefficient=0.504, α=0.05).

Biological Parameters

Fishes

A statistically significant difference in diversity of fishes was found at the control station (23 species) relative to the experimental station (7 species) at the high impact site. Fish abundance was also significantly higher at the control station (156) compared to the experimental station (44). The *hinalea*, the saddleback wrasse, *Thalassoma duperrey* was abundant at all 6 stations.

Fish abundance was lower at the experimental station (960 individuals) while diversity was slightly higher (14 species), relative to the control station (1259 individuals/11 species). This was not found to be statistically significant. The most commonly recorded fishes at the medium and low impact site at all stations were the *uhu*, the red-lip parrotfish, *Scarus rubroviolaceus* and the *hinalea*, the saddle wrasse, *Thalassoma duperrey*.

No statistically significant difference in fish abundance or diversity was found at the low impact site. A total of 581 fishes comprising 9 species were recorded from the experimental station at the low use site. The control station reported more species (16) but fewer individuals (286).

Benthos

As expected, coral cover differed greatly between the experimental and the control stations at the high impact site (correlation coefficient=0.003, α=0.05). Total coral cover at the experimental station was extremely low (1.4%), while the control station exhibited 34.1% coral cover. Invertebrate counts were high at the high use site, consisting mainly of the urchins, *Echinometra mathaei* and *Heterocentrotus mammilatus.* At the control station, 775 invertebrates were enumerated while 529 were reported at the experimental station.

Coral cover was not significantly different between the experimental and the control stations at the medium and low impact sites (Figure 2.9).
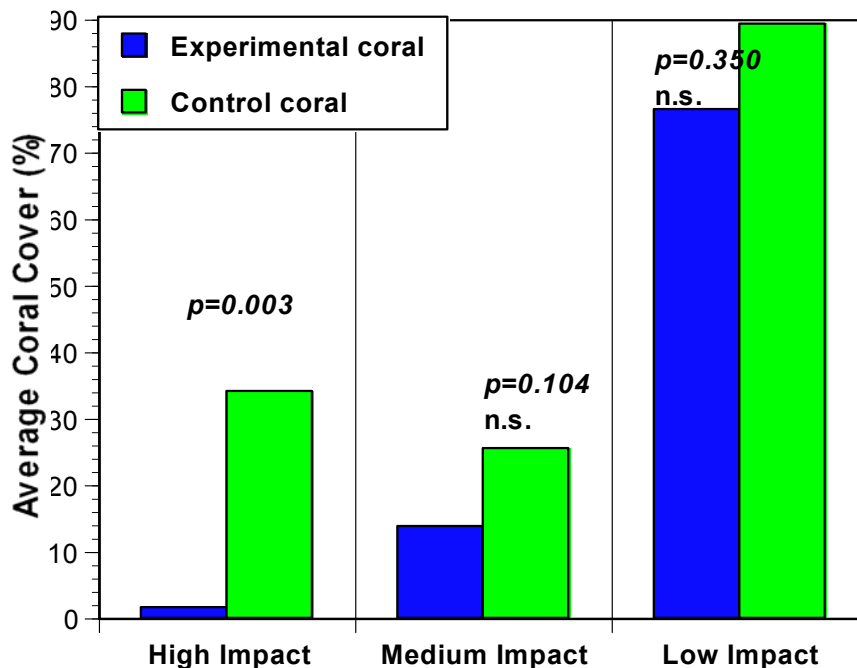

Figure 2.9 Site Comparisons of Coral Cover

The medium impact site showed 13.8% and 25.5% total coral cover at the experimental and the control stations. Extremely high coral cover, relative to the other sites was recorded at the low impact site, with experimental and control stations displaying 76.5% and 89.3%, respectively.

The majority of the remainder of the cover consisted of non-biological substrate. Coralline algae and macroalgae made up only a small percentage of the total at all 3 sites.

2.5   DISCUSSION

This study was originally designed to measure impact of human contact on coral growth. The final result, however, demonstrated that corals die under high impact conditions. A clear progression of survivorship along the gradient of impact is evident. Corals subjected to high levels of stress from trampling exhibit high mortality (Figure 2.4). Since all p values calculated were <0.05, there is less than a 5% chance that these significant differences observed occurred by chance alone.

At sites with medium and low levels of stress, no noticeable effects in growth were exhibited between impacted and non-impacted colonies. This was not a function of sample size. A previously conducted power analysis determined the sampling regime of this experiment would be able to detect a

52

difference in the mean values, using at least seven samples at each station. Sample size was based on this prior test.

It is possible that there is no effect to the growth of corals at medium and low levels of trampling, yet, this was not substantiated in the simulated trampling experiments, that demonstrated significant differences in growth in colonies impacted by trampling only nine times (see Chapter 4).

It is more probable that growth differences were not shown because little impact occurred. The commercial operator at the medium use site minimizes impact to corals by conducting activities in deeper waters away from the reef flat. Those on the reef flat are all required to wear personal flotation devises (PFD's), further minimizing contact with the substrate. The commercial operators frequenting the low use site also provide floatation for skin divers. Long foam tubes (noodles) are used by inexperienced skin divers, while more experienced skin divers not using floatation are less likely to contact the substrate. Time and resources restricted use of in water counts of direct contact with corals, which would be useful in resolving this issue.

A clear pattern of decreasing coral cover with increased use emerged along sites. There was an inverse relationship between percent coral cover and use at sites. Keough and Quinn (1991) also described this gradient along sites with high cover and low use. Community populations at sites with a long history of use are expected to have lower coral cover. This was reflected at the high impact site with <2% coral cover in the impacted area compared to over 34% cover at the station unaffected by trampling.

The intermediate disturbance model's prediction of species diversity at sites with moderate impact was not supported in this study (Connell 1978). The medium impact site exhibited higher coral diversity at the non-impacted station. This is contrary to the belief that an intermediate stage of disturbance is related to an increase in species richness, due to interference in successional patterns. This model also predicts that areas without disturbance and those with intense impact will have low species diversity. The high impact site in this study supports this theory, while the low impact site did not exhibit higher diversity at the control station.

2.6   CONCLUSION

Transplantation is not recommended as a means of restoration as evidenced by this experiment. Corals transplanted in this study suffered high mortality under continuous trampling pressure. Recovery is impossible unless the impact is removed.

Interest in coral reefs as a recreational resource have increased. Consequently, concerns relating to recreational impacts on reefs in Hawai'i have also increased.

This study provides relevant data for management. Determination of rates of damage and recovery in relation to visitor use patterns will provide a quantitative basis for management decisions. Quantified coral mortality can be important in establishing the carrying capacity for these regions. Findings from

this study can apply to other reefs with similar coral community structure that are also areas of concern. The demonstration of causal links between trampling and coral survivorship can support effective management of coral reefs. It is critical that speculation be replaced with data while there is still time to build further management strategies most appropriate for the sustainability of our coral reefs.

CHAPTER 3 QUANTIFYING HUMAN USE

3.2   INTRODUCTION

A large percent of Hawai'i's reefs are easily accessible to the human population, located within close proximity of major urban centers of resident and tourist concentration. Anthropogenic impacts to reefs are thus greatly increased (Gulko 1999). Increased human population pressure on coral reefs can have deleterious effects. Use by residential and visitor populations have increased on both spatial and temporal scales.

Tourism in Hawai'i has grown to nearly 7 million in 1999. The defacto population on any given day is approximately 165,000. With an average stay of 8.7 days, this equates to 58,360,690 visitor days a year. Repeat visitors make up 58% of the total number of people that arrived in our islands in 1999. The typical tourist has made 4 previous trips to Hawaii. Over $11 billion dollars annually is directly attributed to visitors. The multiplier effect of tourist spending is responsible for over one-third of all personal income in the state (Hawai'i Visitors Bureau).

Recreational and commercial use of our coral reef resources are a significant economic asset statewide. Some of the main reasons Hawai'i attracts so many visitors each year is the easy access to numerous, beautiful beaches and the availability of a wide variety of recreational water sports. To meet this demand, there are over 1,000 ocean recreation companies currently doing business in the state. Of the 7 million tourists that visit Hawai'i each year, 85%

use our ocean resources. The 6 million tourists that use the nearshore environment are superimposed on the residential *kama'aina* population of over 1 million, many of whom use the ocean regularly.

The preservation of Hawai'i's coral reef ecosystem is imperative to the continuation of the tourist industry and the sustainability of the marine resources.

Healthy, undamaged coral reefs are a critical resource for the tourism industry in Hawai'i. Thus, management concerns relating to recreational impacts to reefs in Hawai'i have increased yet research about these impacts are sparse.

To provide a link between growth and survivorship of corals and trampling impact by skin divers and waders, human use was quantified at each of the selected sites.

Three sites were selected that ranged along a gradient of trampling impact. Corals were transplanted and monitored for an 11-month period. Growth and survivorship were then measured (see Chapter 2).

Sites

Kahalu'u

High Use Site

Kahalu'u Beach Park, located on the west coast of the island of Hawai'i was designated by the Department of Land and Natural Resources as part of a fisheries replenishment area in 1999. Although aquarium fish collecting is strictly prohibited, shoreline collecting and subsistence and recreational fishing are

allowed. The most frequent activities occurring within the bay are swimming and skin diving. A popular surfing spot is located just outside the protected waters of the bay. According to Hawai'i County Lifeguard statistics, Kahalu'u Beach Park received approximately 380,000 visitors in 1998.

Kāne'ohe Bay

Medium use Site-Checker Reef

During the 11-month survey period, commercial operations were conducted at the experimental station. Mid-Pacific operates an ocean recreation business at this site. Two large catamarans, the Hula Kai and the Ono Mana, along with several runabouts, began operations on Checker Reef in 1992. Activities include windsurfing, jetskiing, canoeing, banana boating, and skin diving. This large full-service operation is allowed a maximum of 6 jetskis, as regulated by the Division of Boating and Recreation (DOBAR). Volleyball was discontinued on the shallow reef flat in March 1999, just prior to the inception of these surveys. Passenger limitation is 150 people per day. Operations are conducted between 9 a.m. and 3 p.m. Monday through Saturday including State holidays. Commercial activity is prohibited on Sundays and federal holidays as mandated by the Kāne'ohe Bay Regional Council. Watersports SCUBA conducts operations on the south side of the reef, outside the confines of the established experimental and control station. Public use is minimal at these stations. Activities observed include kayaking, fishing, and recreational boating.

Low Use Site-Patch Reef 39

The commercial vessels, Dreamer, American Spirit and Barefoot frequent patch reef 39. Hawai'i Recreation Travel is the parent company of Dreamer. American Spirit and Barefoot are part of the fleet owned and operated by Hawai'i Cruises. Dreamer has a passenger limit of 18. American Spirit has a 28 passenger limit and Barefoot can legally accommodate 73 passengers. Limits are imposed by vessel size, not by State regulations for small skin diving operations such as these within Kāne'ohe Bay. As with all commercial activity in Kāne'ohe Bay, they conduct business Monday through Saturday excluding federal holidays. Activity is confined to the hours between 1 p.m. and 2 p.m. Skin diving was the only activity occurring during the survey period. Public use of patch reef 39 is minimal, involving relatively small amounts of boating and fishing activity.

3.2   METHODS

Observer Variation Surveys

To address variability between surveyors, observer variation surveys were conducted prior to implementation of activity surveys. Two independent groups of observers collected data at Kahalu'u Beach Park. Surveys were conducted from the small pavilion located on the north side of the beach park to provide full visual coverage of all activity occurring within Kahalu'u Bay. On June 18, 1999, 16 high school students from the West Hawai'i Explorations Academy counted

the number of visitors and distribution of activity at 9:30 a.m. and 12:00 noon.

Reefwatchers, a volunteer group organized by the Sea Grant extension on the

island of Hawaiʻi, collected data on July 17,1999 at 9:30 a.m., 10:00 a.m., 11:00

a.m., 12:00, and 1:00 p.m. Twelve Reefwatchers participated in the

observational surveys. Identical survey forms and verbal and written instructions

were provided to all observers. A total of 28 individuals participated in the

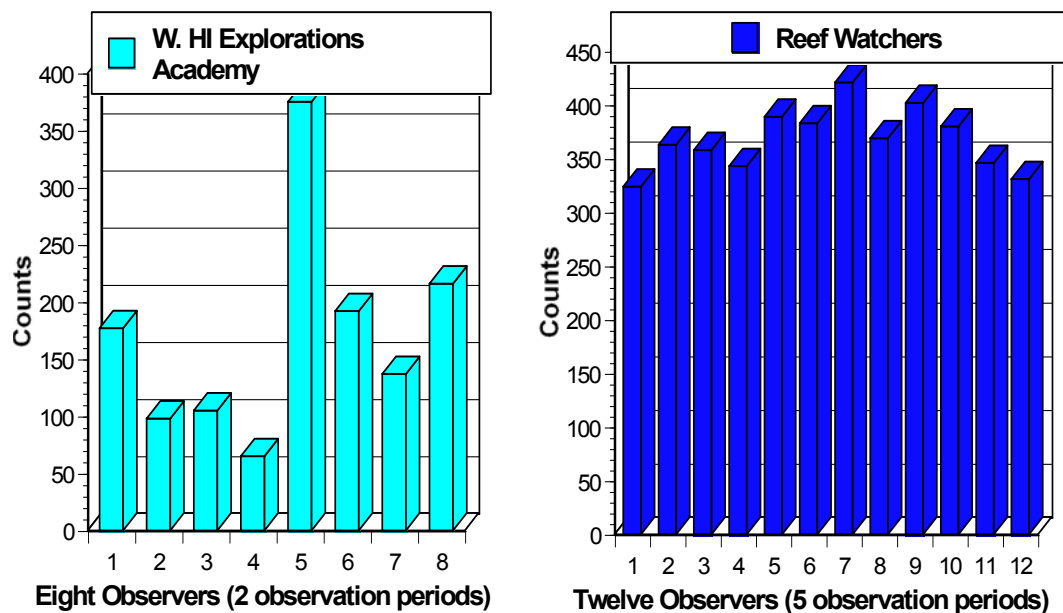surveys (Figure 3.1).

Figure 3.1 Observer Variation in Activity Surveys of Kahaluʻu Beach Park

<u>**Pilot Studies**</u>

To address spatial and temporal differences between sites, pilot studies

were conducted prior to survey implementation. Pilot studies identified daily

fluctuations in visitor numbers, variations in activity levels, and types of activities

occurring in each area. Identification of peak times and days allowed for survey coverage of the maximum number of users. Data from these studies were then used to design surveys at each site. Types of activities occurring at each site were incorporated into survey sheets to distinguish between activity involving possible contact with corals and those occurring in deeper water or on the surface that would not involve substrate contact.

Activity Surveys

Human use assessment was quantified at each site through non-invasive visual surveys and visitor count data obtained through the Hawai'i State Lifeguard Services.   Based on diurnal patterns of use from prior pilot studies, sample days were randomly selected for each of the 3 sites. The calendar year was divided into four seasons to address seasonal variations in visitor activity. These four seasons were delineated in accordance with established meteorological patterns. The following quarters were used in generation of randomly selected survey dates.

Summer: June 21-September 21

Fall: September 22-December 21

Winter: December 22-March 20

Spring: March 21-June 20

Fifteen weekdays, 6 weekends and 1 holiday per quarter were surveyed, providing an equal ratio of actual weekdays to weekend days to holidays. This design was used at the high use site since visitation is not temporally restricted.

In Kāne'ohe Bay, commercial use is restricted to weekdays, Saturdays and state holidays. Since mandated restrictions determine use, two categories for random date selection were chosen. A ratio of days allowing commercial use and days restricting use were used to generate random dates at the medium and low impact sites.

The high and medium use site was surveyed from 8:00 a.m. to 4:00 p.m. on the selected dates. In the first and second quarter it was established that the low use site was visited only between 1:00 and 2:00 p.m. daily except Sundays and federal holidays. Surveys were subsequently restricted to spot checks that included this time period.

Each activity occurring at the sites were recorded separately (see Appendix: activity data sheets). Activity surveys monitored experimental and control stations simultaneously. All surveys were conducted during the period that coral transplants remained in the field to establish a link between growth and mortality and visitor use.

Length of time spent at Kahalu'u Beach Park was also recorded. Individuals and groups of individuals were randomly selected upon arrival. Presence was monitored at 15-minute intervals until departure. Categorical variables included total number of people in each group and the number of children in each group.

3.3   <u>RESULTS</u>

<u>Observer Variation Surveys</u>

Each of the Reefwatchers participating in the survey counted the number of people engaging in specific activities at 5 different times during the day on 17 July, 1999. Cumulative counts ranged from 890 to 1251, with a standard deviation of 97.0.

The West Hawai'i Explorations Academy observers counted people at two times during the day on 18 June 1999. The cumulative counts ranged from 65 to 375, with a standard deviation of 96.8.

<u>Pilot Studies</u>

High Use Site- Kahalu'u

Pilot studies at Kahalu'u Beach Park identified peak activity times occurring between 8 a.m. and 4 p.m. The number of people present on weekdays was lower than the number of people on weekends. Types of activity recorded during this period included swimming, surfing, skin diving, reefwalking, fishing, shoreline gathering and sunbathing.

Medium use Site- Checker Reef

The peak hours of use were identified as between 9 a.m. and 3 p.m. Use was consistent Monday through Saturday. No activity occurred on Sundays

during the pilot study. Types of activities observed included SCUBA diving, skin diving, windsurfing, jetskiing, boating activity and canoeing.

Low Use Site-Patch Reef 39

Activity peaks were determined to be between 1 p.m. and 2 p.m. Monday through Saturday. No activity was observed on Sundays. Boating activity and skin diving were the only activities recorded at this site during this period.

Activity Surveys

All activity surveys were based on information gathered during the pilot studies for each site.

High Use Site- Kahaluʻu

A total number of 158.1 people per hour were enumerated in 8 categories from 18 June 1999 to 14 June 2000. Counts were extrapolated within each quarter to allow for temporal variability. This provided an estimated total of 290,540 users over the period the transplanted corals remained in the field. Relative frequencies are displayed in Figure 3.2.
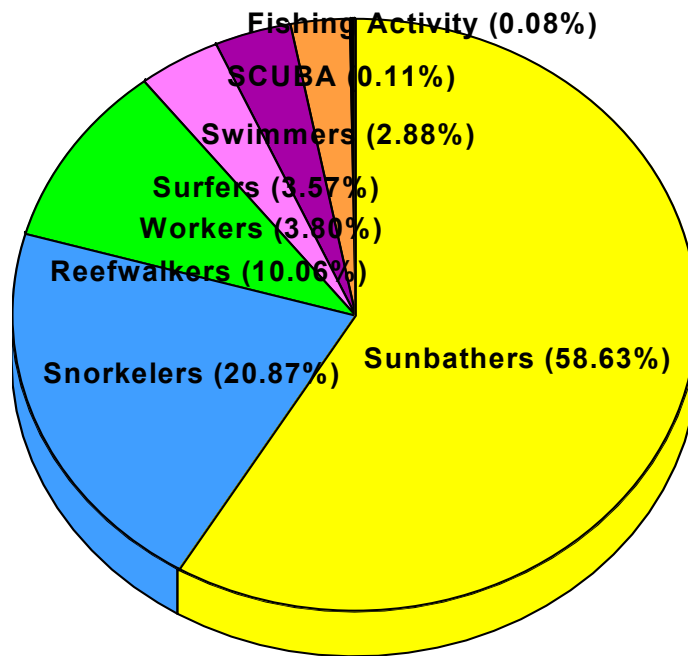
Figure 3.2 Activity Use at Kahaluʻu Beach Park (high use site)

The largest activity category was sunbathing (58.6%), followed in decreasing frequency by skin divers (20.9%), waders (10.1%), employees (3.8%), surfers (3.6%), swimmers (2.9%), SCUBA divers (0.1%), and fishermen (0.1%). The average number of people per hour was the highest in the spring (185.7), with use declining in the winter (175.9), fall (148.6), and summer (122.4). To relate human use to coral mortality and growth, the number of people in the water was extracted from the total counts. More people per hour engaged in activities in the water in the fall (79.4) than in the spring (62.3), winter (57.3) or summer (51.2).

There was significant diurnal temporal variability. A clear pattern of
increasing use was evident. Peaking at noon and declining hourly thereafter
(Figure 3.3).
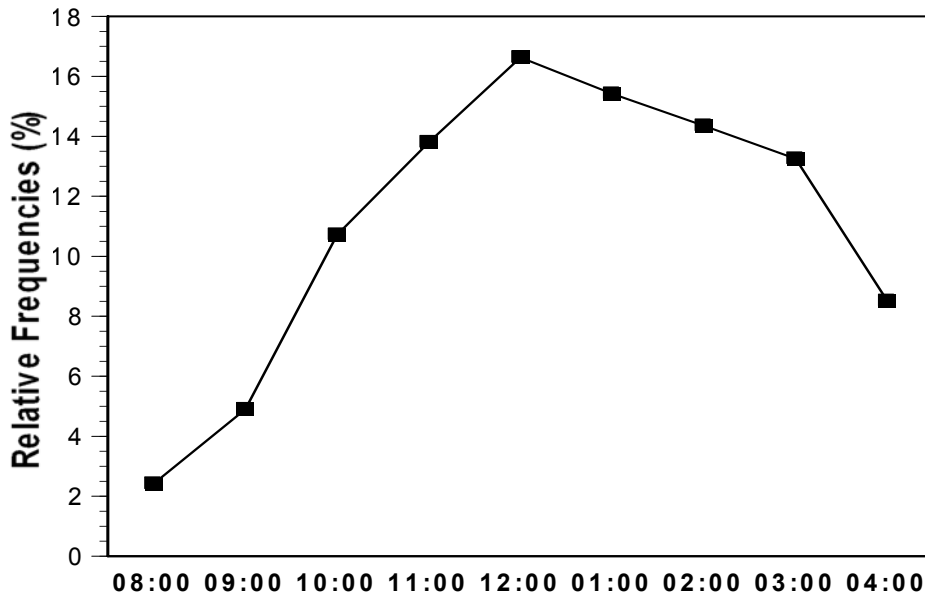
Figure 3.3 Diurnal Pattern of Human Use at Kahaluʻu Beach Park

Relative frequencies of conditional distributions increased throughout the
morning with 2.42% of the daily total present at 8:00 a.m., 4.90% at 9:00 a.m.,
10.72% at 10:00 a.m., 13.80% at 11:00 a.m. and 16.63% at 12:00 noon.
Numbers declined steadily following this mid-day peak with 15.42% at 1:00 p.m.,
14.35% at 2:00 p.m., 13.25% at 3:00 p.m. and 8.51% at 4:00 p.m.

The average length of time spent at Kahaluʻu Beach Park was 2hr. and 28min. There was no statistical difference shown between groups including children (2hr.19min.), and those without children (2hr.42min.). People stayed longer on weekends (3hr.10min.) and holidays (2hr 32min) than on weekday (2hr) (Figure 3.4). No significant seasonal differences in the length of time spent here was detected. Activity at the control station was minimal with a total of 0.09 people per hour.
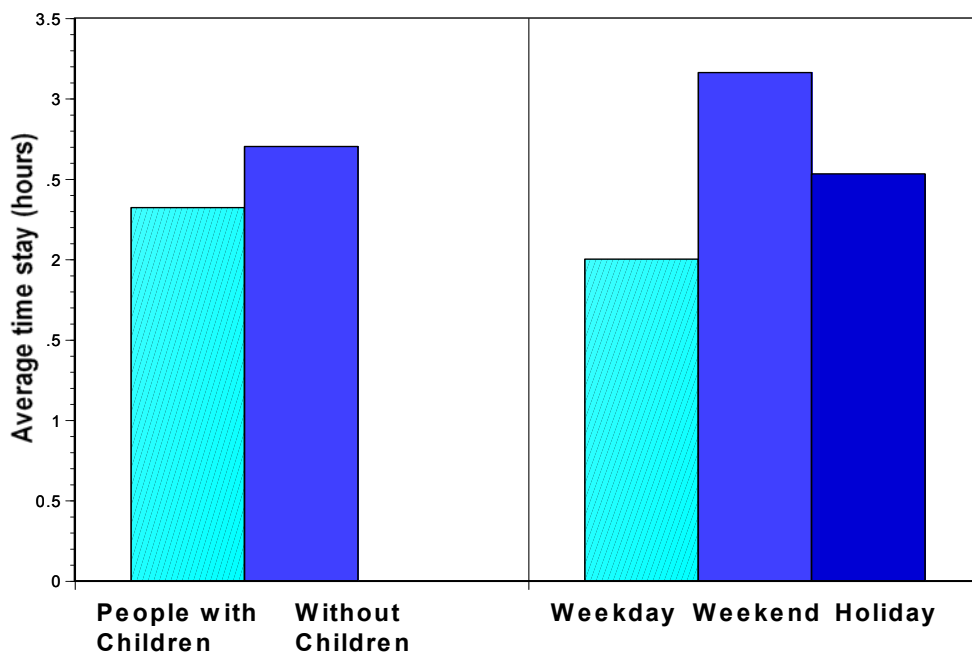
Figure 3.4 Average time stay at Kahaluʻu Beach Park

Comparison with lifeguard data

Total counts obtained from the County Lifeguards for the period from January 1999 to December 1999 were 380,076 visitors to Kahaluʻu Beach Park. This was compared to the observations obtained from this survey, determining

use for this same period at 290,540. Lifeguard counts were 24% higher than the

counts from this study. Variability was high between seasons. During the Fall

counts were within 3% of each other, while the largest difference was during the

summer with 56% difference in observations.

Medium use Site-Checker Reef

Activity levels remained constant from 10:00 a.m. to 2:00 p.m. daily except

Sundays and federal holidays at the experimental station. Activity at all other

times was minimal. The number of people per hour at the experimental station

was higher (23.06) relative to the control station (0.06).

Types of activities in decreasing order were boating 38.49%), skin diving

(13.23%), SCUBA (11.94%), windsurfing (11.07%), banana boating (10.28%),

jetskiing (7.82%), canoeing (6.00%), kayaking (1.09%), and fishing (0.08%).

Relative frequencies are displayed in Figure 3.5.   The number of people in the

water per hour engaging in activities allowing possible contact with corals was

small at both experimental (2.55) and the control stations (0.01).
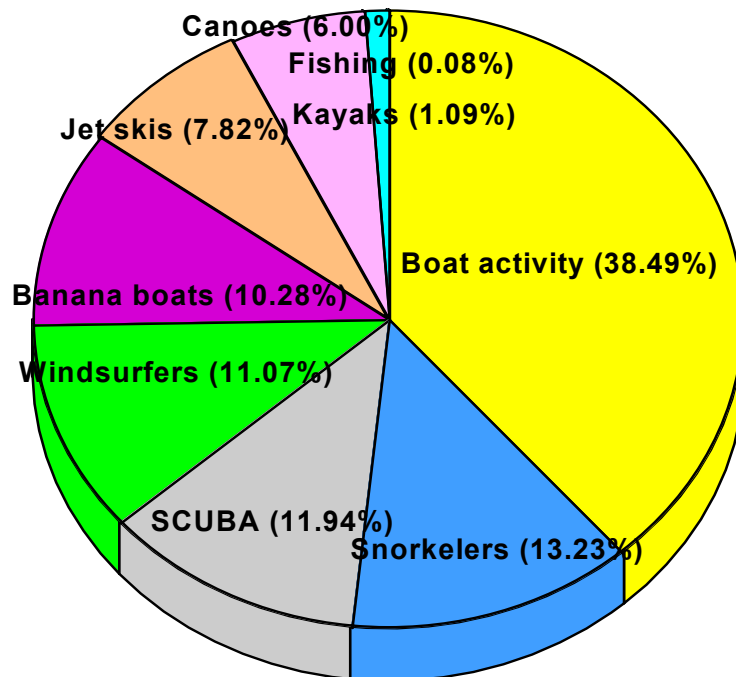
Figure 3.5 Activity Use at Checker Reef (medium use site)

Low Use Site-Patch Reef 39

At Patch Reef 39, peak activity times were between 1:00 and 2:00 p.m. Extremely low numbers of people visited this reef at other times, thus, total number of people per hour (2.64) was very low. The total number of people per hour in the water with possible contact with the corals was much lower (1.08). Most people visiting this reef remained in the boat (68.86%). The relative frequency of skin divers was 30.75%. Fishing accounted for the remainder of the distribution (0.39%) (Figure 3.6). The control station at Patch Reef 42 exhibited minimal use.
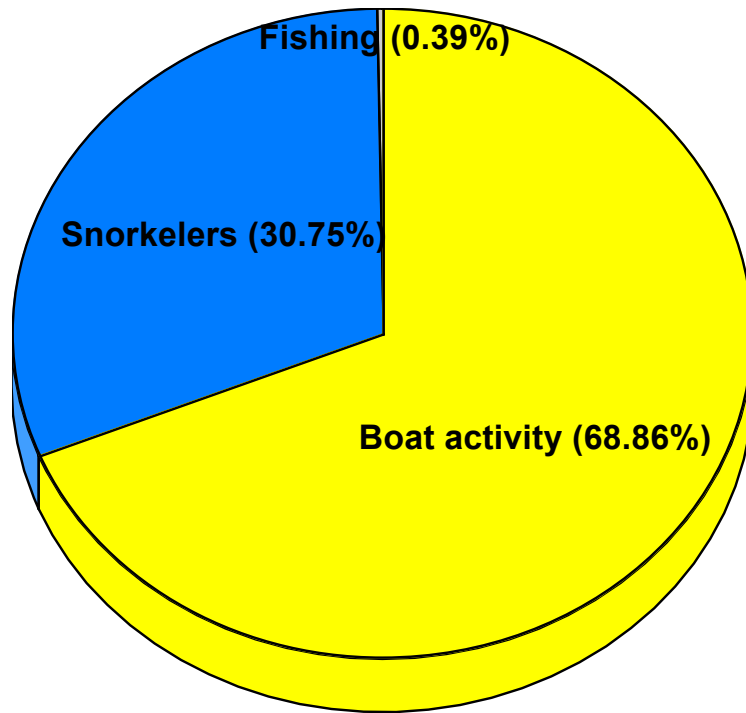
Figure 3.6 Activity Use at Patch Reef 39 (low use site)

3.4 DISCUSSION

Observation variation surveys showed high variability among observers. These surveys were conducted to address issues of precision. To reduce variability, observers were limited to one or two per site. When more than one observer is involved, a method of standardization is necessary to calibrate observer counts relative to each other. Repeated observations, were conducted simultaneously to reduce variability between surveyors.

The large overall difference (24%) between two independent sets of observers, (lifeguards and observers in this study) demonstrates a possible accuracy problem.

There are other problems associated with quantifying observational studies. Attempts to establish links between trampling and coral mortality can be difficult. Since different spatial and temporal patterns emerged at each site, a number of people per hour in the water was derived to relate to the impact of trampling on transplanted corals. The total number of people using a site must be established to determine a relative proportion of people in the water. The next logical step would involve quantifying actual physical contact with corals. Time and cost restraints excluded this option in this survey.

At Kahaluʻu Beach Park, an average of 40% of the people present are in the water during the day. It was determined that at an average of at least 62.5 people per hour in the water, total mortality of corals will occur. Based on observational assessments, it is possible for cryptic corals and sides of massive colonies to survive in high impact areas since trampling does not occur in these regions. All experimental colonies in this study were transplanted to areas exposed to trampling.

The goal of this study was to establish that the explanatory variable, trampling, causes a change in the response variable, the coral. Even with a strong association, the conclusion that this association is due to cause and effect is difficult to ascertain. It is difficult to measure the strength of the relationship between two continuous variables. The probability of obtaining a high correlation between the variables by random chance is extremely high. Aggregation may show significant findings at one level that don't apply at another level. Bias may result through selective observation or observer error.

There can be a true direct cause and effect link or the association may be explained by common response or confounding. The association observed between the trampling impact and the coral damage, may be explained by a lurking variable that may have influential power, such as storm surf. It is difficult to locate a site that meets the human use criteria, where all measured parameters are similar between experimental and control stations. Some biological factors, such as coral cover are negatively correlated with impact. It has been determined that areas with high use have low coral cover while areas with low use exhibit high coral abundance. Since not all extraneous factors can be eliminated, unexplained variation can occur. In this setting, there are many associations among variables that involve complex relationships among interacting factors. It is difficult to control for environmental variability in this situation.

Common response creates an association where there may not be a direct causal link between the two variables. When numerous factors are interacting in the environment their effects can be mixed or compounded to create synergistic effects. These confounding effects can make the assumption of causation difficult. Both the trampling impact and other factors can combine to influence the response of growth and survivorship of corals. This prevents showing a direct effect from trampling alone, since the influence of lurking variables on growth and mortality can not be distinguished from the effects of trampling.

Accuracy of observations can also be difficult to determine. Comparison of comparable data can be used as an indication of accuracy. Lifeguard counts at the high use site denote a range or degree of similarity for contrast with survey data. Another assessment of accuracy, to determine if observed values are representative of the true population, would be to compare observations with a photographic record of the population of interest and adjust accordingly.

Although direct cause and effect can not be established through observational surveys alone, association between impact and mortality is strong. There was 100% coral mortality at the high use site. Trampling is a plausible explanation for coral mortality. Alternative explanations for mortality were ruled out. Flood events and damaging storm surf were not recorded at this site during this period. The higher level of impact was associated with the stronger response and the cause (trampling) occurred simultaneously with the response of mortality.

By itself, even the strong association demonstrated between trampling and mortality (see Chapter 2) is not sufficient evidence to affirm a cause and effect relationship. These community level experiments were an attempt to replicate realism in the affected environment. In conjunction with the colony level manipulative experiments, (see Chapter 4) a direct causal link can be determined and was established.

3.5   CONCLUSION

Human use surveys can be a useful method to show an association between human impact and survivorship of corals. When evaluating the extremes of this population, a negative correlation between use and survivorship was established. When a strong response occurs, as in this study at the high use site, with total coral mortality, a clear relationship between trampling and survivorship is evident. Likewise, no effect on coral survivorship was demonstrated at very low levels of use.

Effects of trampling on growth rates of corals can be more difficult to determine using large-scale community level studies as with human use surveys. When coupled with quantitative evidence from colony level, controlled, manipulative experiments (see Chapter 4), a true cause and effect relationship can then be established.

Observer variation surveys and pilot studies must be integrated into the survey design to provide precision and accuracy. Variability can be high among observers. A method of standardization is needed to calibrate observations and reduce variability. Pilot studies are important to identify temporal and spatial variations that may be overlooked in the survey design.

CHAPTER 4 EXPERIMENTAL TRAMPLING

4.1   INTRODUCTION

Through coral transplantation and quantification of human use, response to trampling at the community level was addressed (Chapters 2,3).   Yet, to establish a causal link between the growth and mortality of corals and trampling, experimental manipulation is required.   Simulated trampling experiments can provided a quantitative baseline to compare the response of trampling in impacted and non-impacted colonies. Restricted on spatial and temporal scales, it can help affirm the link at higher scales by isolating the experimental factor and controlling for other physical, chemical and biological variables that can affect coral growth and mortality. Four dominant Hawaiian coral species were selected to investigate response at the colony level.

These colony level experiments examined effects of trampling from acute impact while the community level experiments (Chapters 2,3) involved chronic disturbance. Human impacts to the natural system can be classified as acute or chronic disturbances. Acute disturbances are episodic disruptions that are of a temporary nature and are not temporally sustained, as in a flood event or oil spill. Chronic disturbances are sustained over time as in sewage outfalls. Trampling can contain attributes of both. Corals may receive periodic stress, a series of repeated pulses or continuous pressure (Keough and Quinn 1991). Recurrent disturbance associated with this type of activity may inhibit recovery due to its persistent nature.

Coral resistance to physical forces are associated with colony size, morphology and the composition and properties of the coral skeleton (Chamberlain 1978, Vosburg 1982). Between colony variation of branch morphology within a species can range greatly. For example, *Montipora capitata* can exhibit a morphological range from plate to highly branched forms. This can affect the range of vulnerability of corals exposed to trampling. Skeletal damage to massive forms may result even though breakage has not occurred. Permanent and temporary damage to tissues may result in a reduction of gametic production or retarded growth when exposed to trampling.

Branch breakage incurred by trampling, is dependent on the applied force of a single event. Pressure is not evenly distributed among branches and is not cumulative, as is tissue damage to polyps (Liddle and Kay 1987).

Fragmentation can be caused by oceanographic disturbances such as currents, waves or storms. Biological disturbances can also produce fragments from contact with sea turtles, fishes and boring organisms or from anthropogenic sources including breakage from trampling, anchors or boat groundings. Trampling forces may affect the top of corals while natural wave forces may be applied in a direction to include the sides of corals (Liddle and Kay 1987). Yet, breakage may not be indicative only of damage from biological or physical disturbances. Some rapidly growing corals may become separated from the parent colony from the pressure of their own weight (Maragos 1972).

Ramets, clonal replicates of the coral colony produced through fragmentation, may be an effective way of increasing survivorship of the coral

76

colony. Certain environmental conditions may not be conducive to the survival of sexually produced planulae yet may allow for survival of fragments. This means of asexual reproduction is especially important for species exhibiting rapid and indeterminate growth, long life spans, large colony size, relatively late sexual maturity, low larval recruitment and limited seasonal reproduction (Highsmith 1982).

The balance between sexual and asexual reproduction depends on environmental as well as physiological conditions. Williams' (1975) Strawberry-Coral model predicts that if substrate is available for horizontal expansion, than resources will be invested in asexual cloning rather than into sexual reproduction.

Evidence that fragmentation has been selected for in many coral species include the fact that spatially many corals occur in high energy regimes, reproduce sexually at a late stage, and exhibit long life expectancies. The diverse morphologies of corals, low skeletal strengths, rapid growth rates and high porosity all support the theory that fragmentation is adaptive. If reproductive success is more frequent than catastrophic, stochastic storm events, than skeletal strength need only reflect stable, predictable conditions. Metabolic energy input into increasing skeletal strength would better be used for reproduction.

There are many advantages to fragmentation as a viable means of reproduction. Propagation by fragmentation should enhance sexual reproductive success by providing additional clones. The probability of mortality is significantly reduced with two or more colonies than with a single colony.

Greater surface area can be attained with 2 or more separate colonies than with one large colony of comparable size, due to morphological restrictions. Fragmentation is also less seasonal than sexual reproduction, allowing for year-round expansion. The large initial size of a fragment, already in the adult form, increases the chance of survival compared to sexually produced larvae. Additionally, fragments are produced in a predictable environment in close proximity to the parent where environmental conditions favored growth of the initial colony. Highsmith (1982) found that fragmentation by corals expands horizontal territories and allows for rapid recovery from perturbations. These may be included in the life histories of some corals to enhance rates of recovery from hurricanes and other natural events. While fragments may be an important means of reproduction on some reefs, this was demonstrated not to be the case in the Maldive Islands, where all broken pieces died (Allison 1996).

Some habitats may not be conducive to colonization by fragmentation. Fragments may be too unstable in high energy environments to effectively colonize these areas. Vertical faces or highly impacted areas may be more likely to be initially colonized by sexual recruits.

Sexual reproduction has advantages in unstable conditions, produces genetically diverse offspring and can act as a mechanism for long-distance dispersal. Coupled with sexual reproduction, asexual reproduction can increase the success of colonization.

All 4 species of corals used in this experiment are in the families that have been reported to reproduce through fragmentation. The abundance and

78

distribution of acroporid and poritid corals are primarily due to fragmentation (Highsmith 1982). *Acropora aspera* colonies are primarily derived through fragmentation in Guam (Birkeland et al. 1979). This has also been well documented in Hawaiʻi for some dominant Hawaiian species including three of the species used in this research. *Porites compressa* exhibited significant fragmentation production in Kāneʻohe Bay (Hunter 1988). This species expands horizontally to new locations through fragmentation caused by wave forces (Maragos 1972). Deeper regions can be invaded on slopes when detached pieces descend. Fragments of *Porites lobata* transported during a winter storm were reported to increase percent cover at deeper depths (Dollar 1975). Cox (1992) demonstrated the importance of fragmentation in reproduction for *Montipora capitata* in Kāneʻohe Bay.

Fragment survival has been shown to be influenced by environmental and physiological factors. Abrasion from movement and smothering by sediments have caused high mortality in unattached fragments. Mortality was reduced in fragments that rapidly attached to the bottom (Wallace 1985). Smothering by sediments can be a significant cause of mortality for fragments in close contact with the substrate (Kobayashi 1984).

The geometry of fragments may also affect survivorship. Morphologies in 3 dimensions allow part of the fragment to be removed from the substratum making it less likely to succumb to smothering. Fragment growth rates have also been shown to be heavily influenced by location and species (Maragos 1974). Fragment survival is also size dependent. Highsmith et al. (1980) found 45%

79

survival of large fragments >37.6 cm compared to the overall survival rate of 39%.

4.2   **METHODS**

<u>Site Selection</u>

Moku o Loʻe, located in Kāneʻohe Bay on the windward side of the island of Oʻahu, was selected as the site for the trampling experiment (Figure 4.1). Criteria for site selection included easy access for fieldwork and monitoring and lack of outside disturbance to the site. The University of Hawaiʻi's Institute of Marine Biology, located on Moku o Loʻe, was established in 1951. The island was subsequently designated as a marine protected area where scientific studies are conducted.
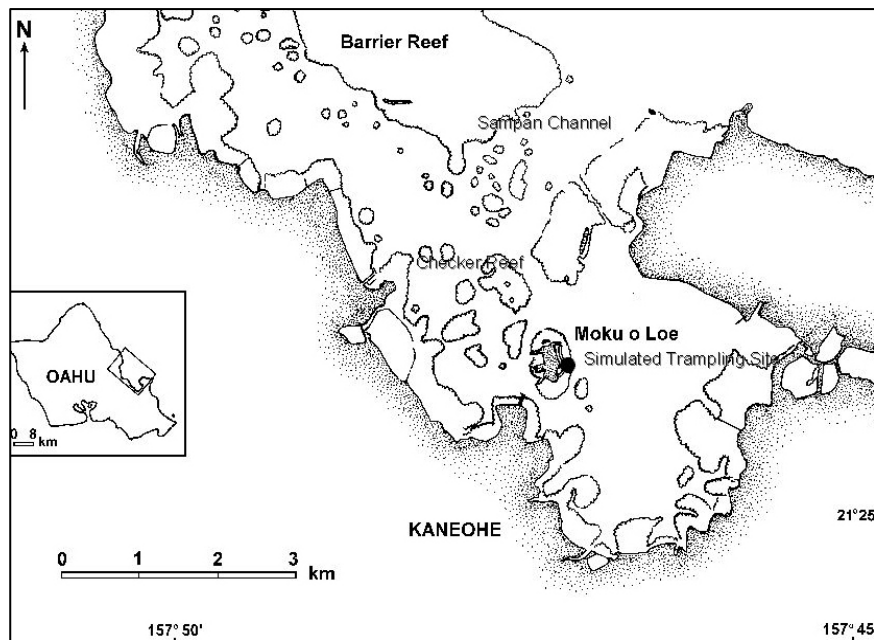
Figure 4.1 Site of Trampling Experiments at Moku o Loʻe Island,

Kāneʻohe Bay, Oʻahu, Hawaiʻi

<u>**Species Selection**</u>

Four species of corals were selected for manipulation, *Montipora capitata* (rice coral), *Porites compressa* (finger coral), *Porites lobata* (lobe coral), and *Pocillopora meandrina* (rose or cauliflower coral). Criteria for selection was based upon the occurrence of the species within Kāneʻohe Bay, domination of these species throughout the state, and the species morphology.

To increase the likelihood of survival, all corals were collected as close to the experimental site as possible. *P. meandrina* and *P. lobata* were obtained from the Sampan Channel (Figure 4.1). *M. capitata* and *P. compressa* were

collected from patch reef 8, more commonly referred to as Checker Reef, just adjacent to Moku o Loʻe (Figure 4.1).

These 4 species of corals are dominant in the Hawaiian Islands. The results from this experiment are not specific to this site and can relate to many areas of concern throughout the state of Hawaiʻi, where the same species composition occurs.

Four diverse forms of corals were selected for the trampling experiments. Rates of disturbance directly attributed to skin divers and waders is highly localized and may not be a severe problem in some habitats due to species morphology. For example, the massive and encrusting forms found in high wave-energy environments are more resistant to breakage than calm-water branched and foliaceous forms. Massive and encrusting morphology and colonies with thick branches have the advantage in being able to withstand physical damage better as a result of their form rather than a property of the physiology of the skeleton (Chamberlain 1978).

Simulated Trampling Experiments

Ten, healthy, undamaged colonies of each species were selected. *P. meandrina* has determinate growth with rates declining as colony size increases (Grigg 1983). Thus, colonies of comparable size were selected. Colonies were sawed in half to allow for genetic diversity and to provide additional statistical power. Half of each colony was placed in the impacted, experimental site while

the other half was placed in the unimpacted, control site. This allowed for paired comparisons of the colonies to reduce added variance due to genetic differences.

Colonies were stained with Alizarin red. This biological stain is incorporated into the tissues of the coral leaving a permanent mark in the coral skeleton. Alizarin powder was dissolved in a small amount of seawater and diffused in 880 liters of seawater in tanks measuring 116.5 x 116.5 x 65 cm in the laboratory. The concentration of the powder was 0.00015 mg/l^{-1}. This is equivalent to 15 parts per million. Higher concentrations have been reported to be lethal. Corals remained in the stain for a period of 8 hours. Reduced calcification rates and stress bands have been reported in corals that were left between 12 and 24 hours (Hudson 1981). Aeration was supplied to tanks during treatment.

Colonies were placed on the reef flat on the windward side of Moku o Lo'e, in a depth that assured no exposure at low tide. Colonies were labeled and attached with wire to 20 plastic plant nursery trays measuring 40 X40 cm each. Corals remained in the field for a 1-year period to allow for seasonal variations in growth, to assure adequate recovery time due to treatment and transfer stress, and to allow for measurable extension rates.

Experimental and control colonies were placed side by side to control for all physical, chemical and biological factors that affect coral growth and mortality. This experimental design assured equal exposure of all colonies to salinity, temperature, depth, light, turbidity, predation and water motion.

The experimental colonies were subjected to trampling until minimal breakage occurred. To simulate impact by skin divers and waders, contact was applied by volunteers wearing dive fins and booties and ranging in weight from 27 kg to 73 kg.

Detached fragments were recovered, measured and sorted into two size classes, <5cm and >5cm. They were placed in plastic plant nursery trays and returned to the field. The probability of survival of colonies and fragments subsequent to exposure to treatment was compared to colonies and fragments in the control group not exposed to damage by trampling to determine survival rates.

Linear extension was evaluated by use of calipers to measure the distances between the permanent pink marker incorporated through staining and the outer most portion of the skeleton. Since growth rates within colonies can be variable, an average of as many measurements as could be obtained was applied. The ratio of the growth rate of a treatment colony to the growth rate of the undamaged control colony was used to determine recovery rates.

4.3   **RESULTS**

Survivorship

Survivorship of all four species of corals following an 11-month recovery period was high (Figure 4.2). There was no significant difference in survivorship between the treatment colonies and the control colonies.

Mortality of one of the 10 colonies in the treatment group of *Montipora capitata* resulted in a 90% survival rate. This 90% survivorship was not significantly different from the 100% survivorship of the control group. Survivorship was 100% in all *Porites compressa* colonies. Mortality of experimental and control colonies was equal for both *Porites lobata* and *Pocillopora meandrina*, with 90% survivorship reflecting the loss of one colony in each group (Figure 4.2).
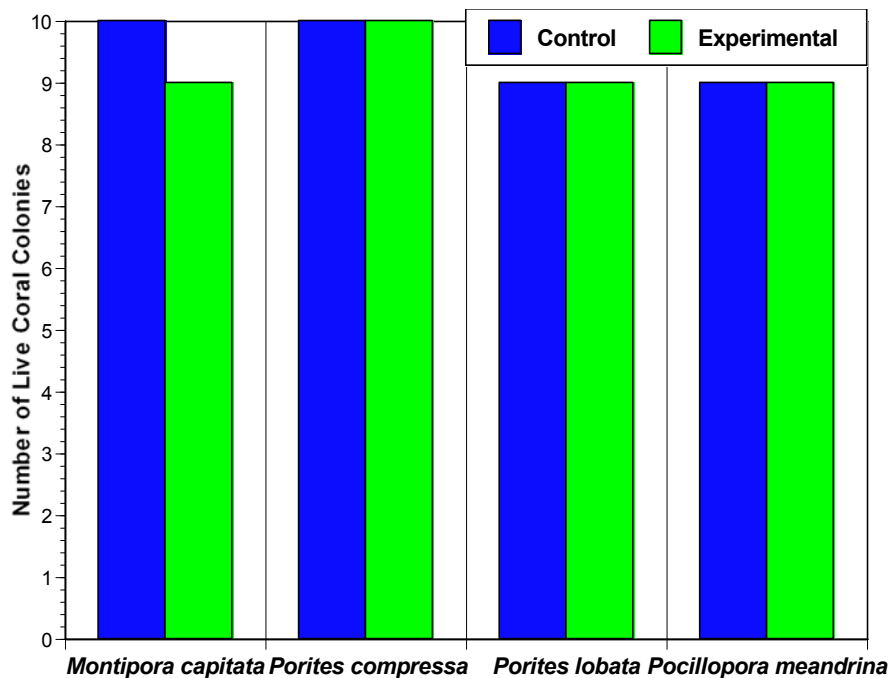

Figure 4.2 Survivorship of Trampled Coral Colonies

<u>Fragment Survivorship</u>

A significant response to trampling occurred, with a progression of damage resulting from the 9 tramplings (Table 4.1 see next page).

Mc=*Montipora capitata* Pc=*Porites compressa* Pl=*Porites lobata*
Pm=*Pocillopora meandrina*

Plot #	11-Aug	12-Aug	13-Aug	16-Aug	17-Aug	18-Aug	19-Aug	20-Aug	20-Aug
	number of fragments produced from each colony								
Pc 1	12	2	1	0	1	1	5	1	0
Mc	1	0	2	1	0	0	0	0	1
Pm	0	1	2	0	0	0	0	0	0
Pl	0	0	0	1	0	0	0	0	0
Pc 2	3	0	5	0	0	0	0	0	0
Mc	11	0	1	0	0	0	0	0	0
Pm	1	0	0	4	1	1	1	0	0
Pl	0	0	0	0	0	0	0	0	0
Pc 3	20	1	1	3	0	1	4	0	0
Mc	16	5	5	0	1	0	1	0	0
Pm	0	0	0	0	0	0	0	0	0
Pl	1	0	0	0	3	0	0	0	0
Pc 4	10	4	2	0	0	0	0	1	0
Mv	5	1	2	0	0	0	0	0	0
Pm	0	0	0	0	0	0	0	0	0
Pl	0	0	0	0	0	0	0	0	0
Pc 5	5	0	2	1	0	1	0	0	0
Mv	8	4	12	0	1	0	0	0	0
Pm	0	1	0	0	0	0	0	0	0
Pl	0	0	0	0	0	0	0	0	0
Pc 6	7	4	3	2	1	4	0	0	1
Mc	22	20	6	18	0	17	0	0	0
Pm	0	3	1	0	0	0	0	0	0
Pl	2	3	0	0	0	0	0	0	0
Pc 7	15	2	0	0	0	4	0	0	0
Mc	11	35	1	0	0	0	0	0	0
Pm	0	0	0	0	0	0	0	0	0
Pl	0	0	0	3	0	1	0	0	0
Pc 8	19	5	0	4	1	0	0	0	0
Mc	7	5	9	5	1	0	0	0	0
Pm	0	0	0	0	0	0	0	0	0
Pl	0	0	1	0	1	0	0	0	0
Pc 9	20	8	0	0	0	0	0	0	0
Mc	21	5	2	6	2	0	0	0	0
Pm	2	0	1	0	0	0	0	0	0
Pl	0	0	0	0	0	0	0	0	0
Pc 10	8	0	2	1	1	0	1	1	0
Mc	29	9	4	0	0	0	1	0	0
Pm	1	0	0	0	0	0	0	0	0
Pl	1	0	6	1	0	0	0	0	0
total	258	118	71	50	14	30	13	3	2
Grand Total	559								
daily %	46.15	21.11	12.70	8.94	2.50	5.37	2.33	0.54	0.36

Pc-total number of fragments			201	Pc-percent of total	35.96
Mc-total number of fragments			314	Mc-percent of total	56.17
Pm-total number of fragments			20	Pm-percent of total	3.58
Pl-total number of fragments			24	Pl-percent of total	4.29

Table 4.1 Fragments Produced in Simulated Trampling Experiment

A total of 559 fragments were recovered, with the majority of breakage, 46%, occurring after the first treatment (Figure 4.3).
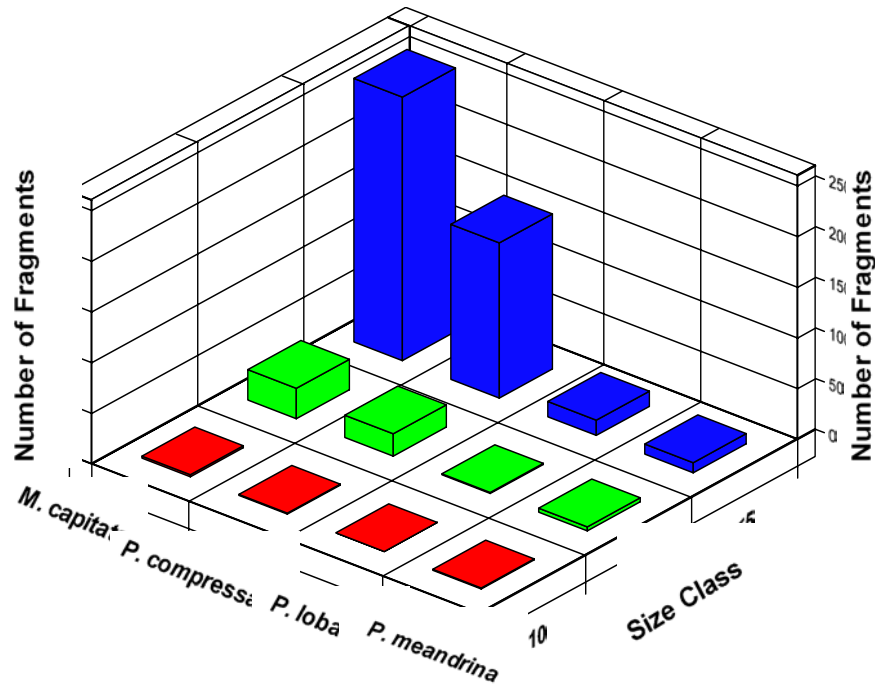
Figure 4.3 Number of Fragments Produced in each Size Class

A significant reduction in fragmentation resulted after the initial impact. Breakage decreased to 21%, 13%, 9%, and 2% of the total with successive tramplings (Table 4.1). Most recovered fragments were <5mm (Figure 4.3).

A large treatment effect was particularly evident in *M. capitata*. The majority of the coral fragments, 56.2%, were collected from this species (Table 4.1, Figure 4.4). *P. compressa* produced 36.0% of the fragments, followed in decreasing order by *P. lobata* with 4.3% and *P. meandrina* producing only 3.6%

of the total fragments recovered (Table 4.1). This is consistent with compressive and tensile tests conducted on coral skeletons to determine strength (see Chapter 4).
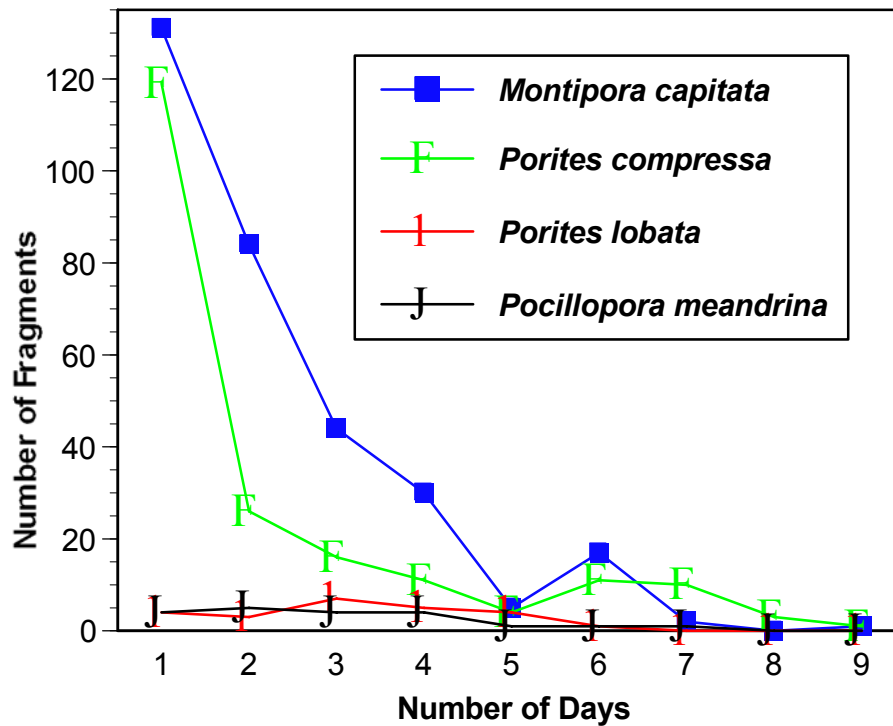
Figure 4.4 Number of Fragments Produced in Simulated Trampling Experiments

Of the 559 fragments recovered following treatment, 439 remained after an 11-month recovery period. The majority of the remaining fragments were comprised of *M. capitata*, 59%, followed by *P. compressa* with 35%, and only 3.4 % and 2.2% of the total from *P. lobata* and *P. meandrina* respectively (Figure 4.5).
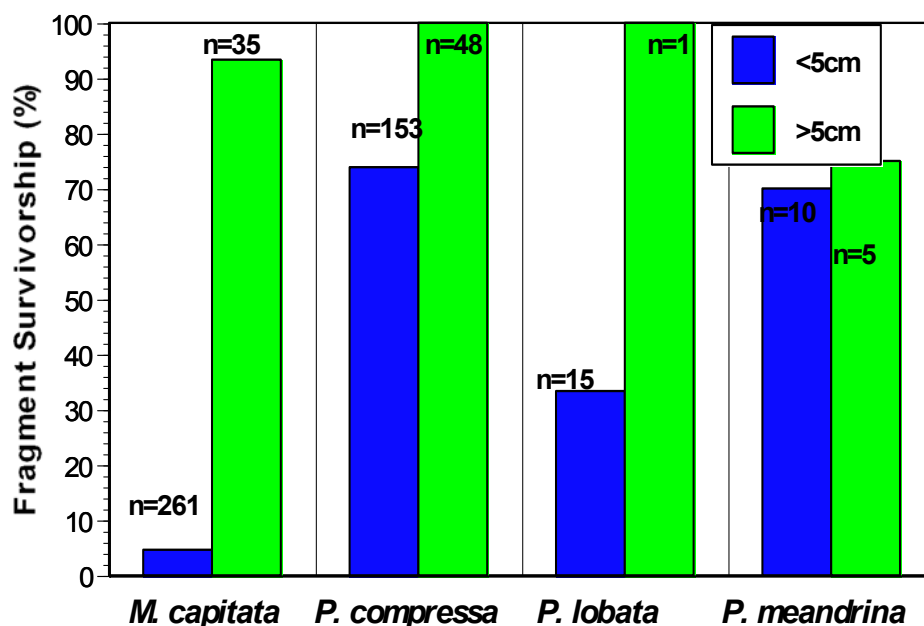
Figure 4.5 Survivorship of Corals in Two Size Classes

The survival of the recovered fragments was clearly size dependent in 3 of the 4 species (Figure 4.5). Only 5% of *M. capitata* fragments that were <5mm survived, compared to 77% of the fragments in the >5mm category. *P. lobata* also followed this pattern of survivorship with only 33% of the smaller fragments surviving and 100% of the larger fragments. All of the larger *P.compressa* fragments survived while only 74% of the smaller fragments remained alive. Only a slight difference in survivorship was found between size classes in *P. meandrina*.

Fragment survival was also species dependent (Figure 4.5). *M. capitata* and *P. lobata* fragments exhibited a low rate of survival in the smaller size class while maintaining a 100% survival rate for the larger fragments. Fragments in the larger size class exhibited 15 times higher survival rates for *M. capitata* and 3 times higher rates for *P. lobata* than the smaller fragments. *P. meandrina* and *P.*

compressa exhibited low mortality in both size classes relative to the other 2 species.

Growth Rates

Retarded coral growth rates in the treatment group indicated a significant response to trampling for 3 of the 4 species tested (Figure 4.6). Results showed statistically significant reductions in growth for the impacted colonies of *M. capitata*, *P. compressa* and *P. meandrina* as compared to the colonies of these species in the control group.
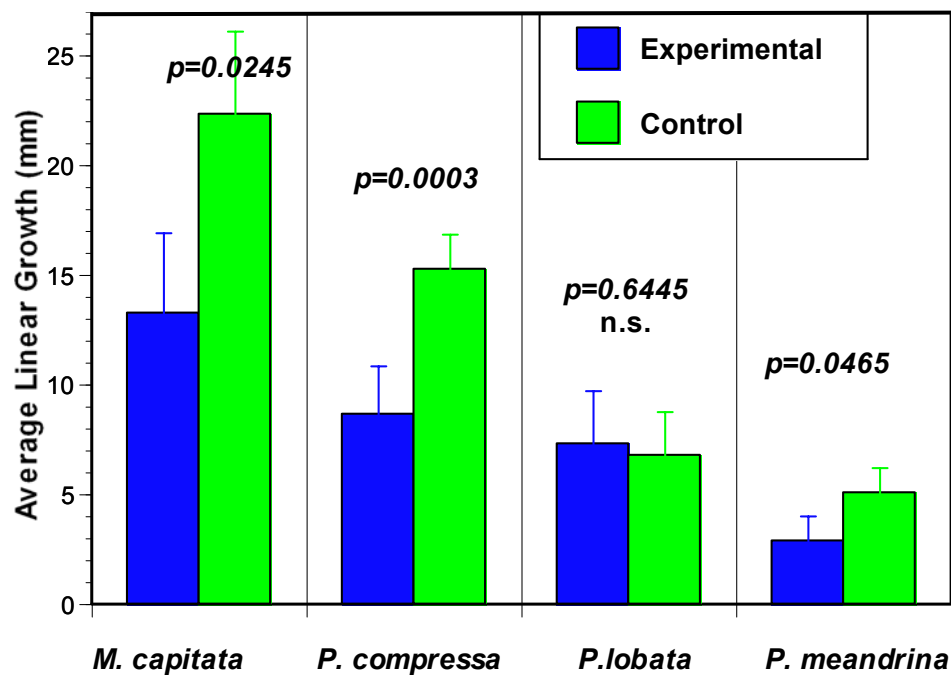
Figure 4.6 Average Linear Extension Rates

Average linear extension rates for an 11 month period for the treatment and control colonies of *M. capitata* were 13.26 mm and 22.32 mm respectively (correlation coefficient = 0.0245, α = 0.05, Figure 4.6). The growth rates of impacted colonies of *P. compressa* averaged 8.65 mm, while linear growth of unimpacted colonies averaged 15.26 mm (correlation coefficient = 0.0003, α = 0.05). *P. meandrina* also showed a significant difference in linear growth of colonies, with the treatment group averaging 2.88 mm and the control group averaging 5.07 mm (correlation coefficient = 0.0465, α = 0.05). Only colonies of *P. lobata* exhibited similar growth between experimental and control corals, resulting in average linear extension rates of 7.30 mm in the trampled group and 6.78 mm in the group that was not subjected to trampling (correlation coefficient = 0.6445, α = 0.05). Paired comparisons of clone mates of *M. capitata*, *P. compressa*, and *P. lobata* showed higher average linear growth rates in all control colonies, except 2 colonies of *P. meandrina* (Figure 4.7).
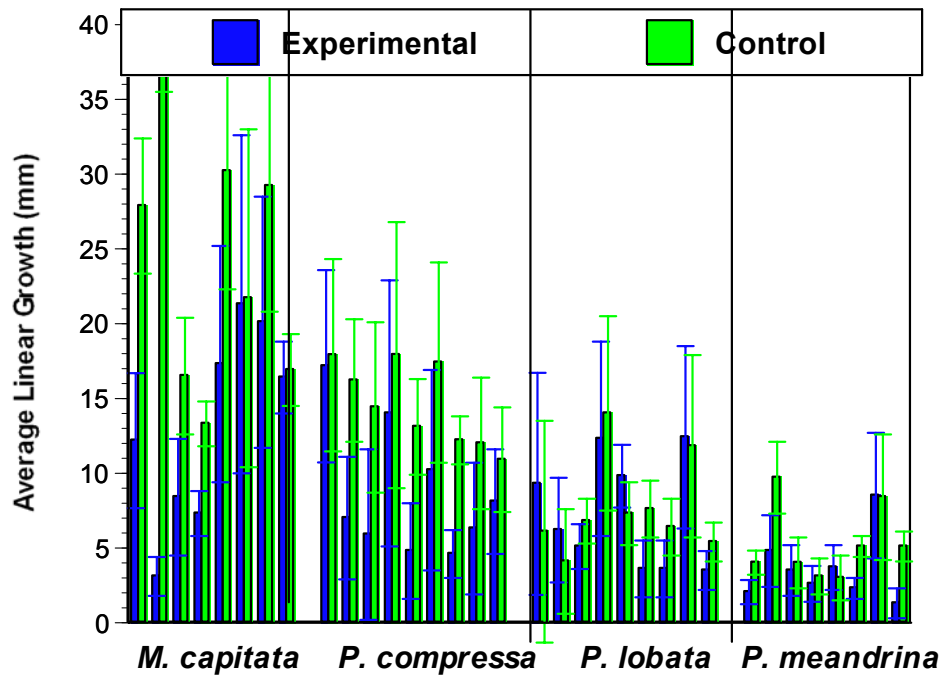
Figure 4.7 Paired Comparisons of Linear Growth

4.4   **DISCUSSION**

Trampling impact can inflict damage to corals at both sub-lethal and lethal levels. High mortality was recorded from trampling at Heron Island in Australia, reducing the coral cover from 41% to 8% in a short period (Woodland and Hooper 1977). Similar damage to algal assemblages was also reported from South New Zealand (Schiel and Taylor 1998). Several studies found that even low levels of trampling can severely damage reef habitats (Brosnan and Crumrine 1994, Brown and Taylor 1999).

Direct and indirect effects of trampling can affect mortality, tissue damage, growth rates, reproductive success and community structure. Brown and Taylor (1999) demonstrated a loss of colonizable habitat subsequent to trampling, to

reefs in north-eastern New Zealand. Tissue damage in *Porites lutea* was described by Liddle and Kay (1987) in studies on the Great Barrier Reef in Australia.

To quantitatively address the responses of trampling, a resistance, survival and recovery model has been proposed by Liddle and Kay (1987). The parameters associated with trampling impact are defined as the following:

Resistance: the amount of force or the number of impacts required to produce breaks in the coral skeleton or a specified amount of polyp damage and death.
Survival: the probability of survival of a fragment or colony after a given amount of damage.
Recovery: the ratio of growth rate of a colony or fragment after a given amount of damage to the growth rate of an undamaged colony or fragment.

This experiment investigated the characteristics of resilience and vulnerability to trampling by assessment of resistance, survival and recovery after damage. These 3 responses to impact were assessed and quantified in this study, to compare between species, at the colony level.

Resistance

Breakage response to trampling was significantly different between species. This can reflect a difference in skeletal strength, species morphology or branch arrangement. Morphological variation was shown to be more important

93

than skeletal strength in studies on *Pocillopora damicornis* on the Great Barrier Reef in Australia (Liddle and Kay 1987).

Over 92% of the pieces broken were recovered from *Montipora capitata* and *Porites compressa*. This is consistent with the habitat they inhabit. They often colonize protected, low energy regions. This exposes them to impact from trampling since these are the identical habitats frequented by skin divers and swimmers.

Porites lobata and *Pocillopora meandrina* exhibited very little breakage relative to the other two species. Adaptations to the environment they inhabit resulted in higher skeletal strengths and morphologies more resistant to wave forces. The breakage rates of all 4 species are consistent with their skeletal strength (see Chapter 4).

Survival

Coral mortality in this study was low, resulting in 93% survivorship of impacted colonies compared to 95% survivorship in control colonies. Low mortality was also demonstrated in field experiments in Australia (Liddle and Kay 1987). All 4 species in this experiment were highly tolerant of inflicted damage, suggesting that corals can withstand limited pulse events that allow time for recovery.

Survivorship of fragments is clearly size and species dependent in *Montipora capitata* and *Porites compressa*. Smaller fragments had higher mortality than larger fragments. The sample size for *Porites lobata* and

94

Pocillopora meandrina was too small to allow for proper statistical comparison of size classes since minimal breakage occurred in these species (Table 4.1). This is consistent with other studies showing larger fragments to have a higher overall survival rate (Highsmith et al. 1980), and fragment growth rates to be influenced by species (Maragos 1974).

Fragment survival is determined by both physiological and environmental factors. Since all fragments in this experiment were subjected to identical environmental conditions, variations in species physiology or geometry may account for differences in survivorship between species.

Fragmentation has been demonstrated as an effective and viable means of reproduction in corals. Natural forces such as waves and currents can serve as a mechanism to enhance and expand coral distribution. Yet, anthropogenic impacts of trampling are of limited benefit to reproduction if corals are subjected to continuous disturbance pressure.

Another advantage of fragmentation in corals is their added mobility as mobile coralliths or rolling stones. This phenomena was described by Glynn (1974) for several species of the genus *Porites* and *Pavona*. He argued against physical transport and provided evidence to support transport by browsing fishes in the Gulf of Panama. Movement of fragments allow exposure to sunlight and nutrients on all sides of the fragments, favoring a circular or cylindrical shape. Thus, skeletal accretion may occur on all surfaces. Due to their mobility, they may posses the advantage to expand their horizons by invading areas not available to their sessile counterparts. The fragments in this experiment were not

attached to the substrate during the 11-month recovery period. This resulted in the formation of mobile coralliths from many of the larger pieces.

Recovery

Growth rates were significantly lower in the treatment group *of Montipora capitata, Porites compressa* and *Pocillopora meandrina* than in the corresponding control groups. This demonstrates that although survival can be high following impact, growth in some species of corals can be affected even after a one-year recovery period.

Growth in *Porites lobata* was unaffected by trampling, exhibiting analogous linear extension rates in paired comparisons between impacted and unimpacted colonies. The lobate, massive form of this species may provide protection from damage by physical forces. Coral resistance has been associated with colony and branch morphology along with skeletal composition and size (Chamberlain 1978, Vosburg 1982).

These results demonstrate the need for regional studies, since recovery differs between species. Many areas of the Pacific are characterized by highly branched, delicate acroporid corals not found in Hawai'i. Results from one region can not always be applied to predict damage in another. Regional variations and morphological differences must be considered.

This small-scale experiment at the colony level isolated the trampling treatment. Environmental parameters that affect coral survivorship and growth

were all controlled for in the experimental design. This study, therefore, establishes a causal relationship between trampling and growth. This direct link to the impact also provides a quantitative baseline for these 4 species of Hawaiian corals. Growth comparisons between species provide a baseline for potential damage based on actual created damage.

4.5   CONCLUSION

It is expected that the branching forms of coral will sustain greater damage than massive or lobate forms. Yet, even the species of corals with the highest skeletal strength and the morphology most likely to withstand impact exhibit breakage when subjected to trampling forces.

Corals can recover and mortality can be low once the impact has been removed and a sufficient recovery period allowed. Yet, most accessible near-shore environments throughout the state receive continuous chronic-type impacts with little or no time for undisturbed recovery. This study demonstrated that as few as 9 tramples can produce significant changes in growth even after a nearly one year recovery period.

At tourist destinations, impact is concentrated in a small area and high mortality can occur. Severe consequences for higher trophic levels are inevitable when damage is inflicted upon reefs. As the local population and visitor industry expands, increased trampling pressure will intensify. Marine protected areas, frequented by tourists, are designed to protect the environment and conserve the

resources. Conservation efforts often attempt to maintain natural conditions.

Removal of marine organisms is often prohibited, yet, public accessibility is not

limited. Since even low levels of trampling can inflict damage to coral reefs, it is

in their best interest for coastal management agencies to consider the effects of

trampling to corals in creating policy decisions.

CHAPTER 5: SKELETAL STRENGTHS OF CORALS

5.1   **INTRODUCTION**

The amount of damage incurred from trampling or natural forces in
nearshore environments is related to the skeletal strength of various coral
species and growth forms. High skeletal strength may be an adaptive adaptation
that reduces breakage and mortality caused by disturbance. Wave forces, depth,
temperature, salinity and light primarily influence growth and the community
structure of reefs. The dominant controlling factors on the reefs are these natural
forces. Anthropogenic factors are super-imposed on these major forcing
functions and are important only in areas where wave forces are not the primary
controlling factor. Coral community structure in Hawai'i is primarily controlled by
wave energy, with only about 10% of the coastline not impacted by waves (Grigg
1998). Lagoons and embayments, regions with high water residence time and
low circulation typify these environments. Most reefs are located in deeper,
offshore waters that have the least exposure to anthropogenic impacts.

Species composition of scelaractinian corals is remarkably uniform
throughout the state of Hawaii, but there are great differences in relative
abundance (Coral Reef Assessment and Monitoring Program 2000). Differences
that exist appear to be caused by different patterns of recruitment and
disturbance (Grigg 1983).

The highly branched, fragile acroporid corals are susceptible to breakage
from natural and anthropogenic forces. Hawaiian reefs differ from reefs

throughout the tropical Pacific in that the most dominant genera, *Acropora*, is not found in the main Hawaiian Islands. Complex assemblages of *Acropora* containing numerous species characterize many of the Indo-Pacific reefs. This provides a highly rugose, habitat for a diversity of flora and fauna. Hawaiian reefs lack this additional topographical relief provided by dense, highly branched forms. Often reefs in Hawaiʻi are characterized by a single species of coral that dominates the environment in a particular region (Gulko 1999).

Human induced negative impacts are increasingly affecting coral reefs. These include overfishing, introduced species, eutrophication, sedimentation, pollution and overuse. Problems associated with overuse increase with increasing human populations. For example, coral breakage can occur following direct contact by divers, waders and inexperienced swimmers.

Coral resistance to physical damage is associated with colony size, branch thickness, morphology, geometry, density, porosity, bioerosion, composition and strength of the coral skeleton (Chamberlain 1978, Vosburg 1982). Mechanical strength is just one of many adaptations that are important factors of structural strength in organisms. The interrelationships of these characteristics make them difficult to separate. Different properties may be critical under varying conditions (Wainwright et al. 1976).

Colony size and shape are a result of genetics, physiology, resource availability and habitat location. Corals are subjected to numerous environmental factors. This has led to limitations in size and morphology of colonies and has determined the range of conditions in which certain coral species can survive.

Corals evolved these morphologies long before recent human interactions that result in skeletal breakage (Chamberlain 1978).

Lobate and encrusting morphologies and colonies with thick branches have the advantage of being able to withstand physical damage as a result of their form rather than as a function of the physiology of the skeleton (Chamberlain 1978). The geometric arrangement of branches can also affect fracture rates. Disturbance directly attributed to trampling by humans can be highly localized and may not be a severe problem in some habitats due to species morphology. For example, the lobate and encrusting forms found in high wave-energy environments are more resistant to breakage than calm-water branching and plate-like or foliaceous forms. Between colony variation of branch morphology within a species can range greatly. *Montipora capitata* can exhibit a morphological range from plate to highly branched forms. This can affect the range of vulnerability of corals exposed to breakage. Skeletal damage to massive forms may result even though breakage has not occurred. Consequences of permanent and temporary damage to tissues may include a reduction of gametic production or retarded growth when exposed to trampling.

Annual and seasonal variations in skeletal density occur in response to environmental factors. Density of the skeleton varies within a colony and between heterogenous growth forms. Exposure, latitude, depth and temperature have also been found to correlate with differences in density in corals (Harriot 1997). Skeletal density affects coral tolerance to physical impacts from human contact and natural forces. Density bands in many massive corals are a result of

deposition variations. The carbonate material that living coral tissues deposit reflects alternating periods of slow and rapid growth (Bucher et al. 1998). Skeletal density can also be used to track periods of elevated nutrients or high energy conditions, thus serving as a record of environmental and anthropogenic change. Variation in density also results in differences in skeletal strength.

Material strength significantly decreases with increased porosity. Species or colonies inhabiting high wave energy environments may have lower porosity than those living in less extreme conditions.

Bioerosional damage to corals caused by boring organisms can considerably reduce strength. Colonies of the Caribbean species, *Acropora cervicornis,* that exhibited erosion caused by boring sponges had basal breaking strength that was an order of magnitude lower than non-bored colonies (Tunnicliffe 1979).

To form their exoskeletons, sceleractinian corals extract calcium from seawater and deposit calcium carbonate in the form of aragonite (Wainwright 1963). Another contributory factor to lower skeletal strength in corals is the absence of significant amounts of organic material in the skeleton. The percentage of organics in biological crystalline type materials determines strength of these materials. The strength of some mollusc shells is enhanced considerably by the addition of viscoelastic organics to other shell components.

Skeletal strength is another important factor affecting the magnitude of impacts caused by human induced breakage. Sparse research has been

conducted to determine the skeletal strength of Hawaiian corals. Research has been typically focused on the biology rather than the physics of corals.

This part of the study concentrated on the mechanical strength of four dominant Hawaiian coral species, using both tensile and compressive forces to measure skeletal durability. The four species selected for testing are common species of corals found throughout Hawaii. Hawaiian reefs can be characterized as *Porites* reefs with *P. lobata* and *P. compressa* ranking numbers 1 and 2 as the most widespread species in the state. *Montipora capitata* ranks number 3 and *Pocillopora meandrina* ranks number 6 in total coral coverage (Coral Reef Assessment and Monitoring Program 2000).

No previous research documented the strength of these Hawaiian corals. In the natural environment, many corals fracture in tension (Vosburgh 1977). Compressive and tensile stresses in corals can be caused by forces applied in various directions or by bending due to applied forces. Corals exposed to current or wave impacts are subjected primarily to bending, while those exposed to trampling are subjected to both compressive forces and to bending (Massel 1999).

The applicability of these research results is widespread and diverse. Analysis of compressive and tensile strengths can be used to establish a relationship between skeletal structure and the ability of corals to withstand diver and trampling impacts. Material strength is also useful in interpreting the paleoecology of corals to understand the life habits, ecology, and habitat ranges of fossil corals. Additionally, skeletal strength can be used to predict species

103

composition in areas with known physical forces. Knowing the mechanical properties of corals and their resistance to trampling can assist management decisions when determining carrying capacities and restricting use.

5.2   **METHODS**

The methods and equipment used in this study were consistent with techniques used to determine strengths for industrial materials.

Tensile strength

Healthy, undamaged colonies of four Hawaiian coral species were selected from Kāneʻohe Bay, Oʻahu, Hawaiʻi. All of the corals tested were collected on the same day. *Porites lobata* (lobe coral) and *Pocillopora meandrina* (cauliflower or rose coral) were collected from the barrier reef flat near the Sampan Channel. *Porites compressa* (finger coral) and *Montipora capitata* (rice coral) were selected from patch reef 8, more commonly known as Checker reef in the Central Basin. Both the plate and branching morphologies of *M. capitata* were collected. Colonies were dried for three weeks before preparation. All prisms were cut from dried coral specimens. Depth and width of prisms varied but were accounted for in Equation 1. The length was controlled by the apparatus.

Prisms (6 x 6x 25 mm) were obtained by cutting the coral with a band saw and sanding with a belt sander to achieve reasonable tolerances ($\pm$1mm) (Figure

5.1a).   Two to five colonies were selected from each species and 1 to 11

replicate prisms were cut from each colony. The number of colonies and

replicates was limited by the dimensions of the coral colony and the number of

branches.   Depth, width and length measurements were made using digital

caliper. A modulus of rupture apparatus similar to one used for testing concrete

according to ASTM C 78 was used to apply a traverse load (Figure 5.2). A Sony

digital camera was used to record each test. The scale of this apparatus was

approximately $^1/_{24}$ compared to the apparatus used for testing concrete.
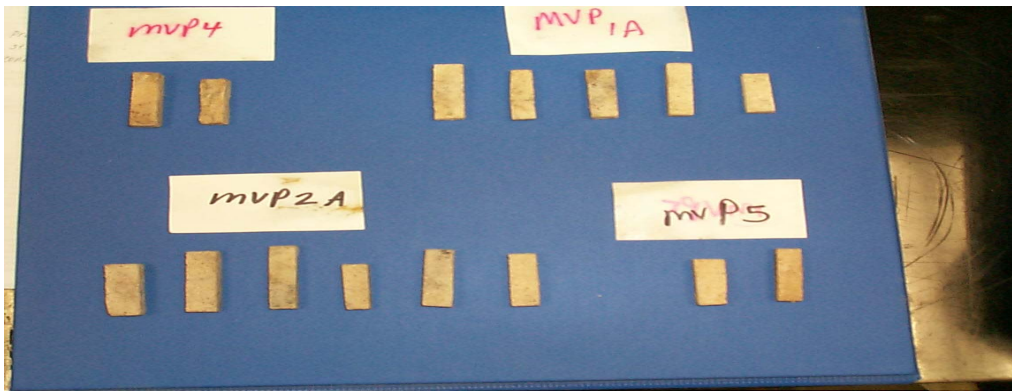
Modulus of Rupture Prisms
(a)

Cores for Compression Tests
(b)

Colonies for Compression
(c)

Figure 5.1 Samples for Tensile and Compressive Material Fracture Tests

Figure 5.2 Modulus of Rupture Apparatus for Testing Tensile Strength

University of Hawaiʻi College of Engineering Material Testing Laboratory

Compressive strength

Compressive strength was evaluated by testing cores cut from colonies and by testing entire colonies of the various species. Cylindrical cores were cut from dried specimens selected by size to provide sufficient volume for coring (Figure 5.1b). Chamberlain (1978) determined that dry, dead coral material reflects the strengths of living corals. Core specimens were tested for *Porites compressa* and *Porites lobata*. The morphologies *Montipora capitata* and *Pocillopora meandrina* did not provide sufficient volume for a core to be obtained.

To obtain the cores, coral colonies were cast with Fixall ® brand plaster, in a cylindrical steel form. Red food coloring was added to the plaster so it could be distinguished from the coral skeletal material. A table lathe equipped with a 19 mm diameter core bit was used to saw the cores. The cores were then cut to lengths between 25 mm and 32 mm. Plaster caps were cast on both ends of each core to ensure that the stress was uniformly distributed over the cross-section during the compression test. An Instron, model 4206, with a 130 KN capacity was used to apply the compressive force at a strain rate of 0.01 min.$^{-1}$ (Figure 5.3).

Colonies were also tested for compressive strength. Colonies selected were of comparable size in an attempt to avoid scaling effects.
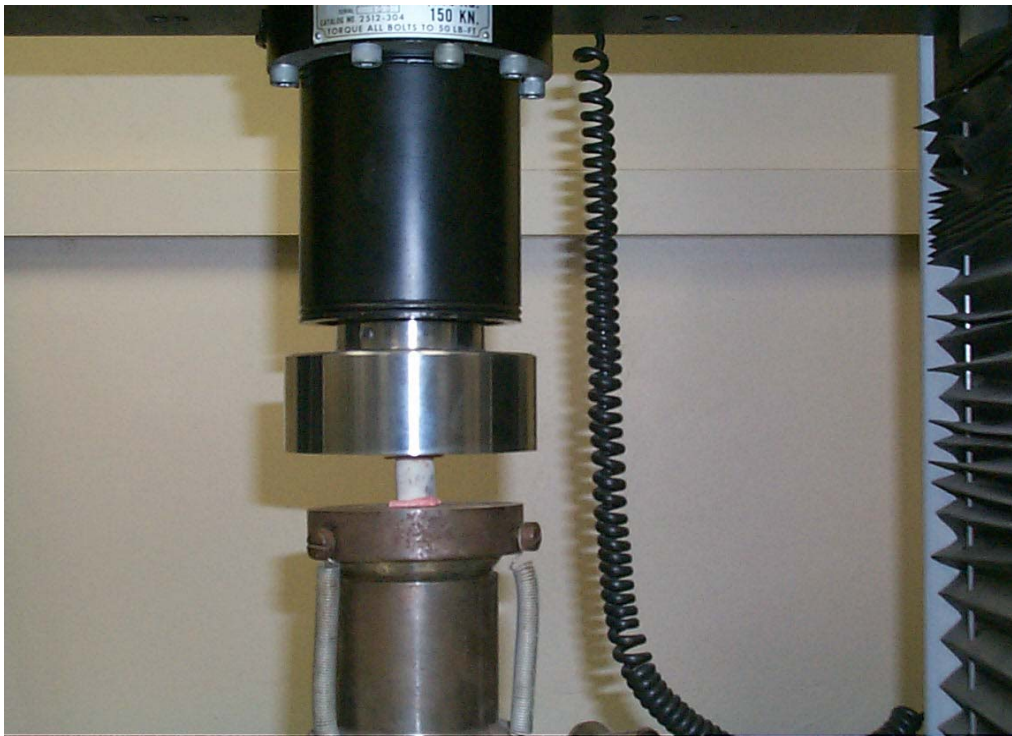
Figure 5.3 Instron Instrument for Compressive Measurements

University of Hawaiʻi College of Engineering Material Testing Laboratory

To prepare colonies for compression tests, each colony base was cast in concrete to assure an upright position during testing (Figure 1c). A 200x200x25 mm neoprene pad was placed between the coral and the load head to simulate a diver's fin or ocean footwear and distribute the load over the colony. The load was applied by lowering the load head at a rate of 0.25 mm/min (the same rate used for testing cores). This load rate was slow enough for inertial effects to be neglected.

Colonies with branched morphologies tended to fracture in tension caused by bending of the branches. Colonies with lobate morphologies fractured in compression. Calculation of the stress generated for the compression fractures is complex due to the geometry of the coral. However, the fracture load for the one specimen that failed in compression was in excess of 1500 lbs./6700 N, much greater than the expected weight of a human. A graph of load versus compressive strain was plotted for each specimen during testing (Figure 5.4).
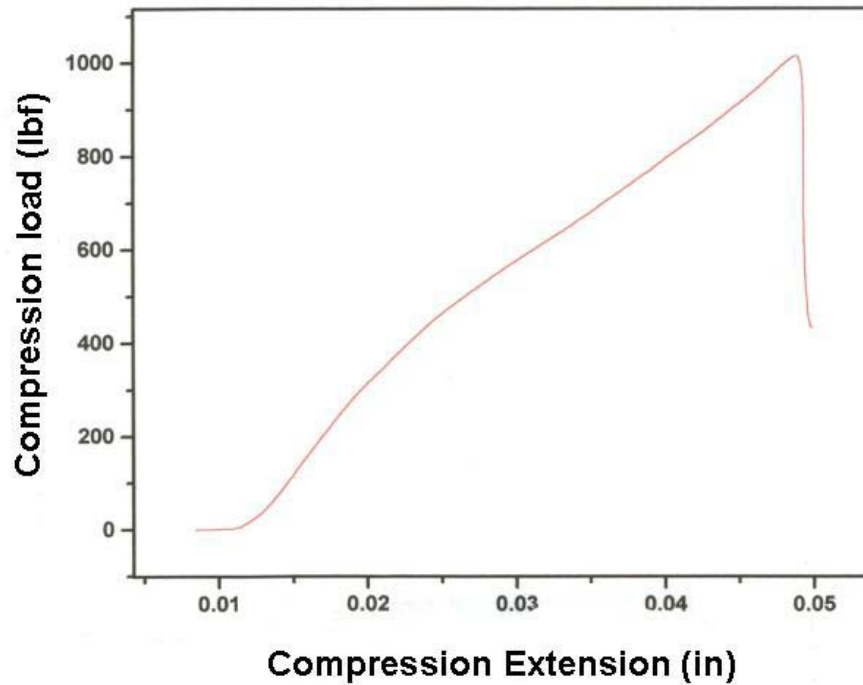
Figure 5.4 Compressive Load for *Porites lobata* in Colony Compression

Analyses

Modulus of rupture tests were performed on 6x6x25 mm prisms to provide a scaled version of ASTM C 78. Data from these tests were used to compute tensile strength for each of the prisms using the following equation:

$$R = \frac{PL}{bd^2} \qquad (1)$$

where R is the tensile strength (modulus of rupture) in MPa, P is the load applied to the specimen in N, b is the width of prism, and d is the prism depth.

Compression tests performed on cores were used to determine the compressive strengths of the corals. Compressive strength may be calculated as:

$$f = \frac{P}{A} \tag{2}$$

where f is the compressive strength in MPa, P is again the load applied to the specimen in N, and A is the cross-sectional area of the core.

Fracture stresses obtained by subjecting colonies to compression were calculated with the following equation:

$$\sigma = \frac{Mc}{I} - \frac{P}{A} \tag{3}$$

where σ is the fracture stress in MPa, P is the load in N, A is the cross-sectional area at the location of the fracture, M is the bending moment in N-m determined by multiplying the applied load by its moment arm, c is the distance from the neutral axis to the extreme fiber at the location of the fracture, and I is the moment of inertia in m^4.

To compare differences in skeletal strength between species, a one-way analysis of variance was used.

5.3   **RESULTS**

Compressive strengths were greater than tensile strengths (Table 5.1). This result is consistent with many materials, including corals that tend to be stronger in compression than in tension.

Species	Tensile Strength (MPa) (mean ± SD)	Range (MPa)	Compressive Strength (MPa) (mean ± SD)	Range (MPa)
Montipora capitata Plate morphology	2.7 ± 0.94 n=12	1.8-4.7	–	–
Montipora capitata **Branched morphology**	3.5 ± 1.49 n=20	0.7-5.9	–	–
Porites compressa	5.3 ± 1.20 n=21	2.9-7.0	6.3 ± 1.58 n=5	4.0-8.1
Porites lobata	6.2 ± 0.93 n=20	4.4-7.5	15.8 ± 5.55 n= 14	8.1-32.1
Pocillopora meandrina	7.0 ± 4.11 n=5	2.5-11.2	–	–

Table 5.1 Tensile and Compressive Test Results

Pocillopora meandrina exhibited the greatest structural strength for both the tensile and the compressive tests. This species was followed in decreasing order by *Porites lobata, Porites compressa and Montipora capitata*. Modulus of

113

rupture results were consistent with compression test results, and all tests
following this order of species ranked by skeletal strength (Table 5.1).

All four species were compared in tensile strengths. Compression of
cores were limited to *Porites lobata* and *Porites compressa* due to lack of
sufficient material in the other two species to accommodate the core diameter.
Colony compression results excluded *Porites lobata,* that consistently exhibited
compression failure due to its lobate morphology.

Modulus of Rupture

There was less variation within colonies than between colonies (Figure
5.5).

Tensile Strength in Megapascals (MPa)

12

0

| M. capitata plate n=15 | M. capitata branched n=35 | Porites compressa n=21 | Porites lobata n=20 | Pocillopora meandrina n=5 |
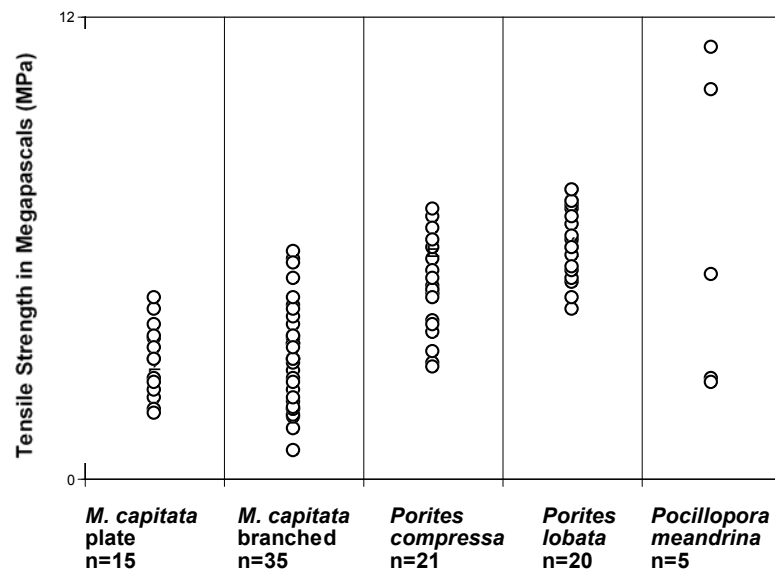
Figure 5.5 Variation in Tensile Strength

Two morphologies of *Montipora capitata* were tested. Of the four species
tested, *M. capitata* required the least amount of load to cause breakage (Figure
5.6). Stress ranged from 1.8 to 4.7 MPa, accepting loads ranging from 19.4 to

223.5 N (1.8 to 22.8 kg). Modulus of rupture values for the plate form, 2.7 MPa,

was not significantly different than the modulus of rupture for the branched

morphology, 3.5 MPa (Table 5.1).
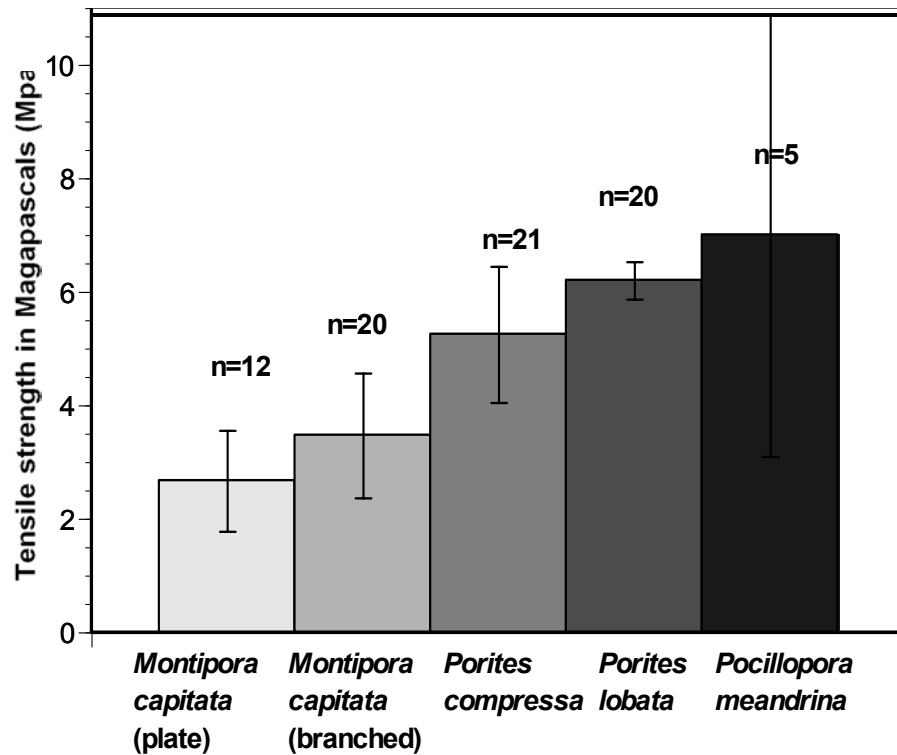
Figure 5.6 Modulus of Rupture Tests to Determine Strength of Corals

Twenty-one prisms were used to test tensile strengths in *Porites*

compressa. Modulus of rupture values ranged from 2.9 to 7.0 MPa, accepting

loads ranging from 59.2 to 304.1 N (6.0 to 31.0 kg) with an average value of 5.3

MPa.

115

Fracture of *Porites lobata* occurred at an average stress of 6.2 MPa, ranging from 4.4 to 7.5 MPa, with an n=21. Load ranged from159.1 to 296.8 N (16.2 to 30.3 kg).

Pocillopora meandrina had the greatest modulus of rupture values. The variation in tensile strength ranged from 2.5 to 11.2 MPa, with an average strength of 7.0 MPa. Loads ranged from 73.8 to 210.2 N (7.5 to 21.5 kg (Table 5.1). Depth, width and sample size of prisms were significantly smaller than other species due to size limitations and fracturing during preparation.

Compression

All four species were evaluated with compression tests. Differences in mean strength between species were statistically significant (one-way ANOVA F=10.89 P=0.13). Cylindrical cores, uniform in size, were used to test compression in *Porites lobata* and *Porites compressa.* As with aggregate based industrial materials and bone, corals exhibit a tendency to be stronger in compression than in tension. Other marine organisms, including molluscs, echinoderms, crustaceans and cnidarians also exhibit higher compressive strengths than tensile strengths. *P. compressa* and *P. lobata* demonstrated compressive strength of 6.3 and 15.8 Mpa respectively. Remaining consistent with modulus of rupture tests*, P. lobata* ranks above *P. compressa* in skeletal strength (Figure 5.7). *P. compressa* showed very little within species variation.
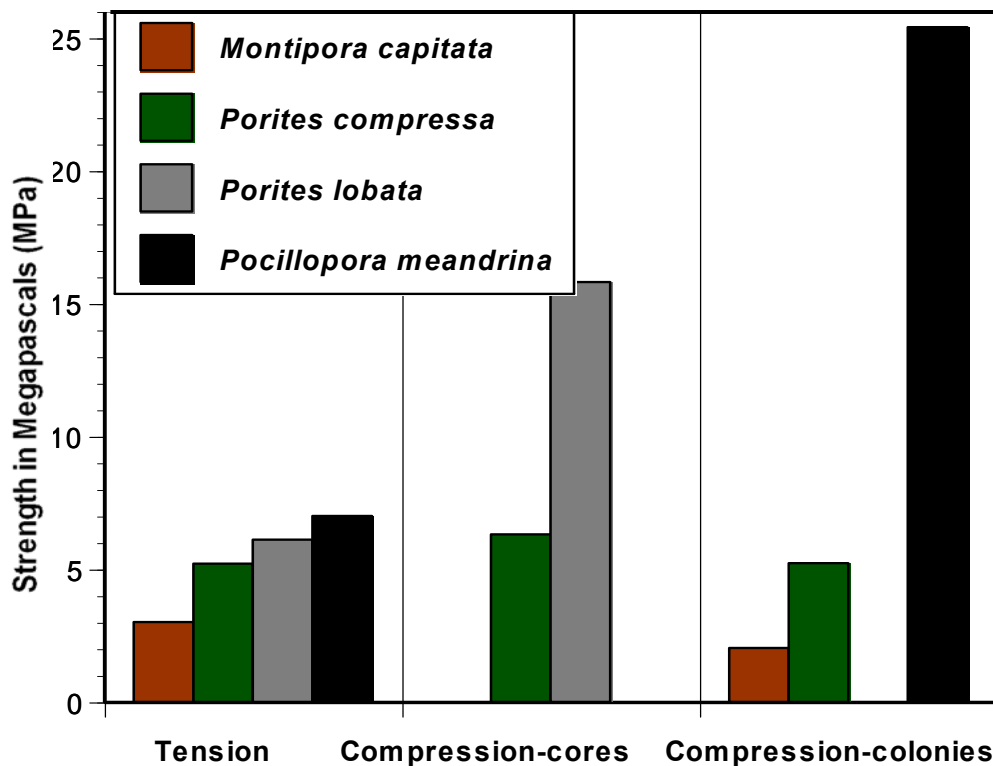
Figure 5.7 Comparison of Skeletal Strength of Hawaiian Coral Species

The load required to induce breakage ranged from 1155.4 to 2339.5 N (117.8 to 238.5 kg) in *P compressa* to 1931.0 to 6450.3 N (196.8 to 657.5 kg) in *P. lobata*, exhibiting very little overlap (Table 5.1).

Tests of compression of colonies used all 4 species. *P. lobata* failed in compression while the other three species produced tension failures. Colonies with branching morphologies tended to fracture in tension caused by bending of the branches. The colony of *P. lobata* with a lobate morphology fractured in compression. Calculation of the stress generated for the compression fracture is complex due to the geometry of the coral. However, the fracture load for the one

specimen that failed in compression was in excess of 6700 N, much greater than the expected weight of a human (approximately 670 N).

As with prior tests, the rank among species with respect to strength remained constant (Figure 5.7). *M. capitata* was the weakest with an average strength of 2.0 MPa, followed by *P. compressa* with an average strength of 5.2 MPa, and *P. meandrina* demonstrating the strongest skeletal strength of 25.4 MPa.   *M. capitata* and *P. compressa* accepted average loads of 241.1 N (24.6 kg) and 444.7 N (45.3 kg) respectively, with very little overlap. Little within species variation occurred (Table 5.2).

Species	Mean Fracture Load (N)	Range (N)	Fracture Strength (MPa) (mean $\pm$ SD)	Range (N)
Montipora capitata Plate	–	–	–	–
Montipora capitata Branched	241.1	61.8-454.3	2.0 $\pm$ 2.85 n=4	0.2-5.1
Porites compressa	444.7	76.9-758.9	5.2 $\pm$ 2.27 n=5	0.9-32.5
Porites lobata	6689	–	–	–
Pocillopora meandrina	1963.8	898.0-2441.4	25.4 $\pm$ 1.38 n=3	12.68-22.75

Table 5.2 Mechanical Strength Test Results (coral colonies)

5.4   **DISCUSSION**

All specimens were dried before testing. Dried, dead skeletal material is representative of living corals in response to fracture stress. Substances lacking substantial amounts of organic matter do not alter their mechanical properties significantly when dry. This was demonstrated with wet and dry mollusc shell samples, where strength in response to stress changed minimally (Taylor and Layman 1972, Currey 1975). In tests on *Pocillopora damicornis*, Wainwright (1963) found the weight of organic matter to be 0.1%. These colonies, collected off Moku o Loʻe in Kāneʻohe Bay, Hawaiʻi were found to contain an unusually pure form of chitin. Other studies found that acroporid corals ranged in organic content from 0.25 to 0.66% (Bucher et al. 1998).

Since coral skeletons contain almost no organics, it is expected that strength is not dependent on the living or dead conditions of the sample.

All tests followed the same order of species strength (Figure 5.7). Based on the results from mechanical tests, the average load required to break *Montipora capitata* is 241.1 N. This ranges from between 75.5 N and 446.4 N. Since these values are substantially less than the average weight of a human (670 N), this species would suffer significant breakage when subjected to trampling. The weight of humans is reduced with buoyancy, although most trampling occurs in very shallow waters.

The force necessary to break *Porites compressa* averages 444.4 N with a range of between 75.5 N and 758.9 N. Standing on this species may or may not result in fracture.

Although the skeletal strength of *Porites lobata* is weaker than *Pocillopora meandrina*, the lobate morphology of this coral makes breakage difficult. *P. lobata* demonstrated a compression failure at over 6688.5 N. *P. meandrina* can withstand forces of between 891.7 N and 2452.5 N, averaging 2006.1 N of pressure to break.

These test results indicate that the weight of the average human (approximately 670 N/70 kg.) will break *M. capitata* and *P. compressa* when the person is standing directly on the colony. *P. lobata* and *P. meandrina* can accept constant, steady forces greater than the weight of an average human.

Coral skeletal strength reflects the wave environment in the regions they inhabit. The results of this study suggest that skeletal strength is an adaptive response to hydraulic stress. Various environmental force and flexural loadings determine skeletal strength development appropriate to the range of turbulent or laminar environments (Massel 1999). The species found in environments with high wave energy were more resistant in stress fracture tests than those residing in habitats indicative of limited energy regimes.   *P. lobata* and *P. meandrina* are found in high energy environments and have skeletal strengths and morphologies that resist breakage. The thick, flat branches of *P. meandrina* and high skeletal strength allow recruitment into high energy environments. Higher coral cover of *P. meandrina* in exposed areas is documented from statewide

monitoring sites (Coral Reef Assessment and Monitoring Program 2000). The most widespread of the Hawaiian species, *P. lobata* can be found from intertidal to deeper waters, with depth limited only by light penetration and suitable substrate. It is common in both protected and exposed regions (Coral Reef Assessment and Monitoring Program 2000). The encrusting or massive forms of this coral make it highly resistant to breakage. Results of skeletal strength from this study are consistent with its ability to withstand strong forces.

M. capitata and P. compressa also inhabit environments consistent with the results found in this study. These species are found in lower disturbance regimes and areas protected from strong wave action. High coverage of these species are found at protected sites throughout the state while extremely low cover of these corals are reported from exposed shores (Coral Reef Assessment and Monitoring Program 2000). The upright form of these species also make them vulnerable to trampling damage. Having adapted to lowered wave disturbance while inhabiting near-shore regions has made these species even more vulnerable to anthropogenic disturbance. Trampling impacts occur most frequently in shallow, protected areas that are favored by skin divers and waders. The low skeletal strength and highly branched morphology of these species make them vulnerable to damage from trampling.

These mechanical test results are consistent with *insitu* trampling experiments conducted on Moku o Loʻe . Following the rank of skeletal strength from both tensile and compressive trials, *Montipora capitata* colonies produced

the most fragments, followed *Porites compressa*. Trampling produced few

fragments from *Porites lobata* and *Pocillopora meandrina* (see Chapter 4).

Mechanical properties of the coral material, morphology, size, porosity,

density and boring organisms all contribute to the resistance of corals to natural

and anthropogenic breakage (Liddle and Kay 1987).

Composition

A comparison with other materials show that coral skeleton is among the

weakest material. Corals rank slightly below concrete and echinoderms (Table

5.3). The high strength of mollusc shell and compact bone reflect significant

levels of a combination of viscoelastic organics and ceramics. Biological

materials with high percentages of organic matter have higher skeletal strength

(Table 5.3). Wainwright et al. (1976) found the strength of skeleton can be

augmented by particular combinations of viscoelastic materials. Crystalline

composites without organic properties exhibit very low tensile strengths. These

include industrial materials like concrete, stone, glass, cast iron and numerous

other artificially produced materials (Chamberlain 1978, Massel 1999).

Group	Tensile Strength (MN/m^2)	Compressive Strength (MN/m^2)	Organics (%)
Biological Materials			
Corals	3-7	2-25	.02-.2
Molluscs	5-121	88-270	5
Echinoderms	27-58	48-96	1
Vertebrates-Human Bone	140-190	210	50
Engineering Materials			
Granite		52	0
Concrete	3-5	20-40	0
Steel	450-800	450-800	0
Aluminum	600	600	0

Table 5.3 Compressive Strengths for Biological Skeletal and Industrial Materials.

Results for coral strength from present investigation. Echinoderm data from Curry (1975). Granite data from Wainwright et al. (1976). All other data as described in Chamberlain (1978).

Porosity

Porosity in coral skeleton also contributes to its lower strength along with other structural factors. Corals exhibit high porosity. Solid compounds have more material per unit volume than highly porous materials (Chamberlain 1978). This makes corals weaker than denser materials of comparable chemical composition. With less material per unit volume, corals compare advantageously to solid industrial products like concrete and granite. Porosity and skeletal strength in corals is inversely related (Wainwright et al. 1976, Chamberlain 1978). Bucher et al.(1998) determined the range of porosity for Acropora species to be between 33% and 70%.

Modification in porosity can be achieved by thickening thecal walls or septa. Inorganic marine cements can also be introduced into the spaces in the skeleton, thus reducing porosity and thus increasing skeletal strength (Gvirtzman and Friedman 1977). This modification occurs more frequently in older sections, which are normally located near the base of the colony, thus providing additional support where the skeleton is most affected by hydrodynamic forces. Corals live within their skeletons and therefore must provide space for the tissues. Thus, low porosity skeletons may be incompatible with accommodating large polyps.

Morphology

Skeletal strength is not independent of other structural characteristics. Colony size and morphology combine with mechanical properties to provide protection against natural and anthropogenic forces.

Morphology of corals plays an important role in fracturing due to stress exerted by weight or hydrodynamic forces. Natural catastrophic events, such as hurricanes have left massive or encrusting forms intact while decimating corals of branched morphology (Stoddart 1963, 1965).   In a similar manner, human induced trampling can cause damage to tissues without physical breakage in massive forms (Liddle and Kay 1987)

Geometry

The adaptive significance of the skeletal architecture of corals also include the influence of the geometry of the colony. Force is applied to highly branched

124

colonies primarily through bending or tension while force is applied to massive forms through compression. Increased skeletal strength would be more important to branched colonies, as increased strength can be achieved by massive forms through geometry (Chamberlain 1978). Branch arrangements are also important to survival. Vertical branches may minimize fractures more than horizontal orientation. Large colonies with elongated, thin branches have more surface area for hydraulic forces to act upon.

Bioerosion

The strength of the skeleton can be further decreased by bioerosion. Boring organisms can weaken the skeleton by increasing voids. When occurring in the basal region, a substantial decrease in strength results. Breakage strengths decreased an order of magnitude over corals displaying no bioerosion in *Acropora cervicornis*, where 75% were found to contain boring sponges (Tunnicliffe 1979).

Fragmentation

Among marine biological materials, corals rank low in strength. Other adaptations may help minimize mortality. Natural fragmentation may be an adaptive factor used as a life history strategy. Highsmith (1982) found that fragmentation by corals expands horizontal territories and allows for rapid recovery from perturbations. These may be included in life histories of some corals to enhance rates of recovery from hurricanes and other natural events.

125

5.5   **CONCLUSION**

Corals developed in habitats free from anthropogenic stresses, thus skeletal strength reflects the physical forcing functions in each regime. Mechanical properties of the skeleton helped to determine the range of habitats and conditions corals could be exposed to. The sequence of vulnerability of corals to trampling impacts is consistent with the skeletal strengths of these species, indicating an adaptive response to disturbance. Susceptibility to trampling will continue to increase as recreational activities chronically overlap with coral habitats.

The applicability of this research is widespread and diverse. Analysis of compressive and tensile strengths can relate to skeletal structure and the ability of corals to withstand diver and trampling impacts. Material strength is useful in interpreting the paleoecology of corals to understand the life habits, ecology, and habitat ranges of fossil corals. It can also be useful in predicting species composition in areas with known physical forces. Knowing mechanical properties of corals can also assist management decisions when determining load carrying capacities and restricting human use.

CHAPTER 6 CONCLUSIONS

6.1   Objectives

The primary objective of this research was to quantify the impacts to corals caused by trampling. This objective was realized through *insitu* and laboratory controlled experimentation. The secondary objectives necessary to fulfill the overall objective were met to varying degrees.

- **Demonstrate whether or not there are impacts to coral reefs by skin divers and waders.**

This objective was met through large-scale community level studies involving coral transplantation and quantified human use surveys (Chapters 2 and 3). High coral mortality was linked to high levels of human use. Small-scale colony level, manipulative experiments demonstrated reduced growth rates in corals impacted by trampling establishing a cause and effect relationship between trampling and growth (Chapter 4).

- **Determine the degree of coral mortality directly related to these impacts.**

The exact degree of coral mortality was not quantified by this research. Total mortality occurred at use levels of 350,000 people/yr. Mortality was not shown to be significant at very low levels of use. Further research is needed to narrow this range by surveying additional sites along the gradient of impact to quantify the exact degree of mortality.

- **Evaluate the growth rates of coral subjected to trampling.**

This objective was met through simulated trampling experiments (Chapter 4). Experimentation showed that growth rates of *Montipora capitata* (rice coral), *Porites compressa* (finger coral), and *Pocillopora meandrina* (cauliflower or rose coral) were significantly lowered by low levels of trampling, while *Porites lobata* (lobe coral) exhibited no adverse effects in growth.

- **Establish baseline data for two popular skin diving sites.**

Baseline data was established for two stations in Kahaluʻu Bay, two stations on Checker reef (patch reef 9), patch reef 39, and patch reef 42. Physical and chemical data include water motion, salinity, temperature, and turbidity. Biological parameters involved baselines of percent cover, diversity, and species lists of fish, macroalgae, corals, and substrate types.

- **Provide a baseline for potential damage at other areas of concern throughout the state.**

This study provides results that can be used as indicators of potential damage throughout the state. The four species of corals tested, rank 1st, 2nd, 3rd, and 6th in abundance in the main Hawaiian Islands (CRAMP 2000). Data concerning these species can thus relate to most near-shore environments in Hawaiʻi. The dominant species of corals in the area of concern relate to the mechanical properties of the coral skeleton to help determine the conditions and environments that these corals can be exposed to and their ability to withstand impact. For example, *Montipora capitata* and *Porites compressa* require force less than the weight of a human for fracture to occur.

128

These results provide a valid representation of some of the influences that affect coral vulnerability. A simple rapid assessment of the area of concern can be undertaken to determine its vulnerability to trampling. Pressure indicators can identify change in coral due to environmental pressure. By integrating these predictive indicators, information about both the present and future state of corals can be derived. All indicators are based on empirically quantified, scientifically derived data that provides influential power to detect near-shore coral damage.

Results have established that at 350,000 people/yr. corals are not sustainable (eg. Hanauma Bay 1 million people/yr.). Regions with low impact (<50,000 peo/yr) may exhibit retarded growth rates but mortality can be low.

Other previously established factors that can affect coral vulnerability include species morphology, branch geometry, wave exposure, and depth. Combined with results from this study, these factors can help predict future damage. These combined indicators of vulnerability, encompass the main scope of the problem of trampling and can help to provide a baseline of potential damage for the state of Hawaiʻi.

- **Determine breakage strength and rates for dominant Hawaiian corals.**

Skeletal strength was determined in controlled laboratory experiments for four dominant species of Hawaiian corals (Chapter 5). Rates of breakage were documented in simulated trampling experiments for these four species through enumeration of fragments (Chapter 4). Mechanical breakage results were linked to rates of breakage to establish a relative rank of vulnerability to trampling.

6.2   <u>**Hypotheses**</u>

These hypotheses outlined the predicted outcomes of this project. Evidence against the null hypothesis (no difference or no effect) was found in three of the five hypotheses.

- **Significant negative impacts to corals will be demonstrated at the high use site.**

Strong validity was established for this hypothesis. No evidence of survival of transplanted corals was documented after 8 months in the field at the high use site.

- **Mortality of corals will increase with increased skin diving activity.**

This hypothesis was confirmed through quantified human use surveys and coral transplantation. A pattern of survivorship with increased use emerged. At the three levels of use, mortality increased from 30% to 45% to 100%.

- **Growth rates of corals and increased human use are inversely related.**

This hypothesis was not quantitatively substantiated. Growth rates of corals were not determined at the high use site due to total mortality. No significant differences in growth were found at the lower use sites. Growth rate evaluation from simulated trampling experiments was not conducted along a gradient of impact. Thus, a relationship between growth and levels of use was not established.

- **Recovery of Hawaiian corals from trampling damage is rapid once the impact has been removed.**

 This was not established due to lack of mortality in simulated experiments. Although no mortality occurred, growth retardation was evident even after an extended recovery period (Chapter 4).

- **Corals with highly branched morphology possess lower skeletal strength than massive, lobate forms.**

 This proved to be a valid statement concerning branch form. *Montipora capitata* and *Porites compressa* that exhibit highly branched character, demonstrated lower skeletal strength in laboratory tests relative to less branched species such as *Porites lobata* and *Pocillopora meandrina* (Chapter 5).

6.3   RESEARCH SUMMARY

1. Community Level Transplantation Experiments

1.1   Survivorship

- Extensive damage can occur at sites with high human use. Continuous impact results in total mortality.   The effects of trampling caused statistically significant reductions in the number of surviving transplanted colonies.   A clear progression of coral survivorship along a gradient of impact is evident. Survivorship dropped from 70% at the low impact site to 55% at the medium impact site. Total mortality (0% survivorship) was reported from the high impact site after only 8 months and less than 200,000 total visitors/63 people in the water per hr.

131

1.2   Transplantation

- Transplantation is not recommended as a means of restoration unless the impact has been removed. Corals transplanted in this study suffered high mortality under continuous trampling pressure.

1.3   Physical and Biological Parameters

- Coral cover and fish abundance is significantly lower in areas impacted by human use than in unaffected areas. This was reflected at the high impact site with extremely low coral cover (1.4%) and fish abundance (44) in the impacted region compared to over 34% coral cover and 156 fishes recorded at the station unaffected by trampling.

- The intermediate disturbance model's prediction for species diversity was not supported in this study. The belief that an intermediate stage of disturbance is related to an increase in species richness, due to interference in successional patterns and that areas without disturbance and those with intense impact will have low species diversity was not consistent for all sites.

- Water temperature did not exceed the thermal limits of corals at any of the sites between May 1999 and May 2000. Decreased growth rates and increased mortality are not expected to occur in less than 1-2 days for elevations of 3^oC to 4^oC above summer ambient temperatures and several weeks at elevations within the 1^oC to 2^oC range.

2. <u>Quantifying Human Use</u>

2.1   Quantified Observational Surveys

- Attempts to quantify trampling can be difficult using human use surveys alone. Measuring actual physical contact with corals or designing controlled, manipulative experiments are necessary to establish a cause and effect relationship between trampling and coral growth or mortality.

2.2   Pilot Studies

- Preliminary surveys must be integrated into the survey design to provide precision and accuracy. Pilot studies are important to identify temporal and spatial variations that may be overlooked in the survey design.

2.3   Observational Variation Surveys

- Counts between observers can differ substantially. A method of standardization is needed to calibrate observations and reduce variability.

3. <u>Simulated Trampling</u>

3.1   Coral Survivorship

- Coral mortality can be low once trampling impact has been removed and a sufficient recovery period allowed. Yet, most accessible near-shore environments throughout the state receive continuous chronic-type impacts with little or no time for undisturbed recovery.

- Although the area affected by trampling is small, these regions are the most valuable because of their accessibility for recreation.

3.2   Coral Growth

- Direct effects of trampling can affect growth rates. Even brief periods of intense trampling can significantly affect the growth of corals even after a substantial recovery period.

- It is expected that the branching forms of coral will sustain greater damage than massive or lobate forms. Growth in *Porites lobata* was unaffected by trampling. The morphology of this species may provide protection from damage by physical forces.

3.3   Coral Fragments

- Survivorship of fragments is clearly size and species dependent with smaller fragments exhibiting higher mortality than larger fragments.

- The initial trampling impact produces the most damage. Nearly half (46%) of the total breakage occurred after the first of nine trampling events.

- Breakage response to trampling was significantly different between species. Over 92% of the pieces broken were recovered from *Montipora capitata* and *Porites compressa*. *Porites lobata* and *Pocillopora meandrina* exhibited very little breakage.

- The level of breakage for a species is consistent with the habitat they inhabit. Species colonizing protected, low energy regions exhibit significantly higher breakage rates than species inhabiting high wave energy environments.

4. Skeletal Strength

4.1   Breakage Tests

- Mechanical test results are consistent with breakage rates. The strongest corals produced the least fragments in trampling experiments. The order of skeletal strength from weakest to strongest are as follows: *Montipora capitata*, *Porites compressa*, *Porites lobata* and *Pocillopora meandrina*.

- Coral skeleton is among the weakest biological and engineering material. Corals rank slightly below concrete and echinoderms.

4.2   Environmental Consequences

- The weight of the average human (approximately 150 lbs.) will break *M. capitata* and *P. compressa* when the person is standing directly on the colony. *P. lobata* and *P. meandrina* can accept constant, steady forces greater than the weight of an average human.

- Shallow, calm areas that are frequented by skin divers and waders are the same environments inhabited by the species of corals with the lowest skeletal strength and with the highest breakage rates.

- Skeletal strength may be an adaptive response to hydraulic stress. Coral skeletal strength reflects the wave environment in the regions they inhabit. The species found in environments with high wave energy were more resistant in stress fracture tests than those residing in habitats indicative of limited energy regimes.

- The sequence of vulnerability of corals to trampling impacts is consistent with the skeletal strengths of these species, indicating an adaptive response to disturbance.

6.4   **CONCLUSIONS**

The outlined summary of results is directly related to management objectives. Results from this research can assist management decisions when determining load carrying capacities and restricting human use. By establishing a direct relationship between trampling damage and coral growth and mortality, management decisions can be defended using quantified scientific evidence.

A baseline of resources has now been established for three areas that have been designated as areas of concern by the state regulatory agency, the Division of Aquatic Resources.

Impact information and establishment of resources is highly relevant to current issues concerning commercial operations at sites within Kāneʻohe Bay. The results from this study can be used to implement and support the master plan for the area. It can be used as a base for decisions on resource management.

Management agencies have already utilized this study. In line with the objectives of the Division of Aquatic Resources to evaluate anthropogenic impacts, plans within their division are currently being implemented to conduct human use surveys at other areas of concern throughout the state. Preliminary

consultation of the experimental design of the human use surveys developed for this research has already been solicited.

The applicability of this research is widespread and diverse. The scientific community can build on these results in future research in this area. Analysis of skeletal strengths can relate to skeletal structure and the ability of corals to withstand diver and trampling impacts. Coral strength is also useful in interpreting the paleoecology of corals to understand the life habits, ecology, and habitat ranges of fossil corals. It can be useful in predicting species composition in areas with known physical forces.

Some of the general results from this study such as fragment survival and observer variations are globally applicable. On a more local scale, we now have the first quantified data on the effects of trampling damage to corals in Hawai'i. The utility of this can be far reaching and is often unpredictable as evidenced in the following research application on wave modeling.

Direct applications of the results of this research have also been realized within the scientific community. Dr. Kurt Storlazzi of the U.S. Geological Survey is currently developing a computer model to predict wave impacts on near-shore environments. This model will have a considerable impact on the scientific community. Lacking prior measurements of skeletal strength for Hawaiian corals, measurements from this study's mechanical strength experiments have been incorporated into this wave model. These coral skeletal strength results are an important component in calculating damage to corals from wave energy.

APPENDICES

APPENDIX I ACTIVITY DATA SHEET

Zone 1 Experimental Site

Date: **Location:KAHALUʻU**   **Collector:**

Type of Activity	8:00 am Zone 1	9:00 am Zone 1	10:00 am Zone 1	11:00 am Zone 1	12:00 noon Zone 1	1:00 pm Zone 1	2:00 pm Zone 1	3:00 pm Zone 1	4:00 pm Zone 1
Boating Activity									
Boats recreational									
Boats Commercial									
Kayaks									
Canoes									
Thrillcrafts									
Fishing Activity									
Pole and line									
Trolling									
Gillnetting									
Trapping									
Spearing									
Shoreline harvesting									
Water Activity									
SCUBA divers									
Skin divers									
Reef walkers									
Swimmers									
Surfers									
Beach/Shore Activity									
Sunbathers Picnicers									

APPENDIX I ACTIVITY DATA SHEET

Zone 2 Control Site

Date: **Location:KAHALUʻU**   **Collector:**

Type of Activity	8:00 am Zone 2	9:00 am Zone 2	10:00 am Zone 2	11:00 am Zone 2	12:00 noon Zone 2	1:00 pm Zone 2	2:00 pm Zone 2	3:00 pm Zone 2	4:00 pm Zone 2
Fishing Activity									
Pole and line									
Gillnetting									
Trapping									
Spearing									
Water Activity									
Skin divers									
Reef walkers									
Swimmers									

APPENDIX I ACTIVITY DATA SHEET

Date: **Location: Checker Reef**   **Collector:**

DATE and TIME of observations Type of Activity E= experimental station C= control station													
	E	C	E	C	E	C	E	C	E	C	E	C	E	C
Boating Activity Record # of boats and # of individuals example **1/5**													
Boats recreational													
Boats Commercial													
Kayaks													
Canoes													
Bannana boat/tubes # of people													
Windsurfers													
Jet skis													
Fishing Activity Record # of people													
Trolling													
Gillnetting													
Aquarium fish collecting													
Spearfishing													
Water Activity Record # of individuals													
SCUBA divers on platform													
Skin divers													
Volleyball reefwalkers													
Non-water Activity													
Individuals on large catamarans													

APPENDIX I ACTIVITY DATA SHEET

Date: **Location: Patch Reef 39 and 42**   **Collector:**

DATE and TIME of observations Type of Activity 39= experimental station 42= control station													
Patch reef	**39**	**42**	**39**	**42**	**39**	**42**	**39**	**42**	**39**	**42**	**39**	**42**	**39**	**42**
Boating Activity Record # of boats and # of individuals example **1/5**														
Boats recreational														
Boats commercial														
Kayaks														
Canoes														
Fishing Activity Record # of people														
Trolling														
Gillnetting														
Aquarium collecting														
Spearfishing														
Water Activity Record # of individuals														
SCUBA divers														
Skin divers														
Reefwalkers														
Non-water Activity														
Individuals on commercial catamaran														

APPENDIX II   AVERAGE TIME STAY PER VISITOR

Date: **Collector:**   **Location:**

Time		no. of people in group # 1		no. of people in group # 2		no. of people in group # 3		no. of people in group # 4		no. of people in group # 5	
adults	kids										
8:00-8:15am											
8:15-8:30am											
8:30-8:45am											
8:45-9:00am											
9:00-9:15am											
9:15-9:30am											
9:30-9:45am											
9:45-10:00am											
10:00-10:15am											
10:15-10:30am											
10:30-10:45am											
10:45-11:00am											
11:00-11:15am											
11:15-11:30am											
11:30-11:45am											
11:45-12:00am											
12:00-12:15pm											
12:15-12:30pm											
12:30-12:45pm											
12:45-1:00pm											
1:00-1:15pm											
1:15-1:30pm											
1:30-1:45pm											
1:45-2:00pm											
2:00-2:15pm											
2:15-2:30pm											
2:30-2:45pm											
2:45-3:00pm											
3:00-3:15pm											
3:15-3:30pm											
3:30-3:45pm											
3:45-4:00pm											

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